HQ GRANT
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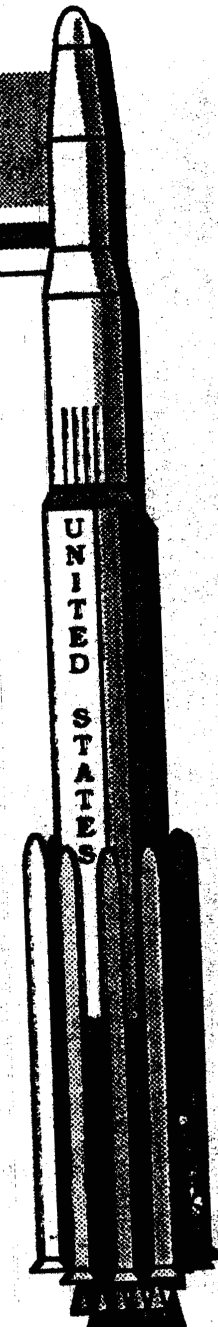
CASP

Center for Advanced Space Propulsion



Annual Report

October 1, 1987
-
October 30, 1988

NAGW - 1195

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CENTER FOR ADVANCED SPACE PROPULSION

ANNUAL REPORT

OCTOBER 1, 1987 THROUGH OCTOBER 30, 1988

NAGW - 1195

THE BOEING AEROSPACE CORPORATION
CALSPAN CORPORATION
ROCKWELL INTERNATIONAL, ROCKETDYNE DIVISION
SATURN CORPORATION
SYMBOLICS
TECHNION, INC.

THE UNIVERSITY OF TENNESSEE - CALSPAN

CENTER FOR AEROSPACE RESEARCH

TULLAHOMA, TENNESSEE 37388

Fred Speer

FRED A. SPEER
DIRECTOR, CASP

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THE UNIVERSITY OF TENNESSEE SPACE INSTITUTE

CENTER FOR ADVANCED SPACE PROPULSION

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I. OVERVIEW

CASP's first year was one of significant growth and inceptive project development. With a mission to initiate and conduct advanced propulsion research in partnership with industry, and a goal to strengthen U.S. national capability in propulsion technology, CASP is the only NASA Center for Commercial Development of Space (CCDS) which focuses on propulsion and associated technologies.

CASP moved to the UTSI Research Park in early February. Furnished with an initial complement of microcomputers, data-fax, and office equipment, the research park location will offer adequate space for PI's and GRAs to work in a productive environment.

Meetings with industrial partners and NASA Headquarters personnel provided an assessment of the unique constraints placed on, and opportunities afforded commercialization projects. Proprietary information, data rights, and patent rights were some of the areas where well defined information is crucial to project success and follow-on efforts. Consultations with our industrial partners resulted in a better understanding of the project restraints and the environment under which the industrial PI's operate.

There were five initial CASP projects. At the end of the first year there are six active, two of which are approaching the ground test phase in their development. Our progress in the current six projects has met all milestones and is detailed later in this report. In summary: we have worked closely with our industrial counterparts and find that our endeavors in Expert Systems Development, Computational Fluid Dynamics, Fluid Management in Microgravity, and Electric Propulsion have been well received.

One project with the Saturn Corporation which dealt with expert systems application in the assembly process, has been placed on hold pending further direction from Saturn. The Contamination Measurement and Analysis project was not implemented since CASP was unable to identify an industrial participant.

CASP investigated additional propulsion and related projects during the year. A subcontract was let to a small business, MicroCraft, Inc., to study Rocket Engine Certification standards. The study produced valuable results; however, based on a number of factors it was decided not to pursue this project further.

II. ADMINISTRATION

2.1 ORGANIZATION

The Center for Advanced Space Propulsion (CASP) is one of two operating organizations of the Center for Aerospace Research (CAR). Beginning October 1, 1987 CAR received a 5-year grant (funded annually) to establish the Center for Advanced Space Propulsion. CAR is a not-for-profit organization formed by the University of Tennessee and Arvin/Calspan (Buffalo, N.Y.) whose administrative offices are co-located with CASP and the Center for Science and Engineering (CSE) in the UTSI Research Park adjacent to the UTSI Campus near Tullahoma, TN. From this location CAR can utilize the facilities at UTSI and have easy access to the test capabilities of the Arnold Engineering Development Center (AEDC) and Marshall Space Flight Center (MSFC) in Huntsville, Alabama.

Figure 2.1 shows the organization of the Center for Advanced Space Propulsion and its relationship to its parent, CAR. The broad technical knowledge provided by personnel of the UTSI and Calspan organizations as well as ready access to test facilities at AEDC and UTSI make CAR a strong parent organization for the Center for Advanced Space Propulsion.

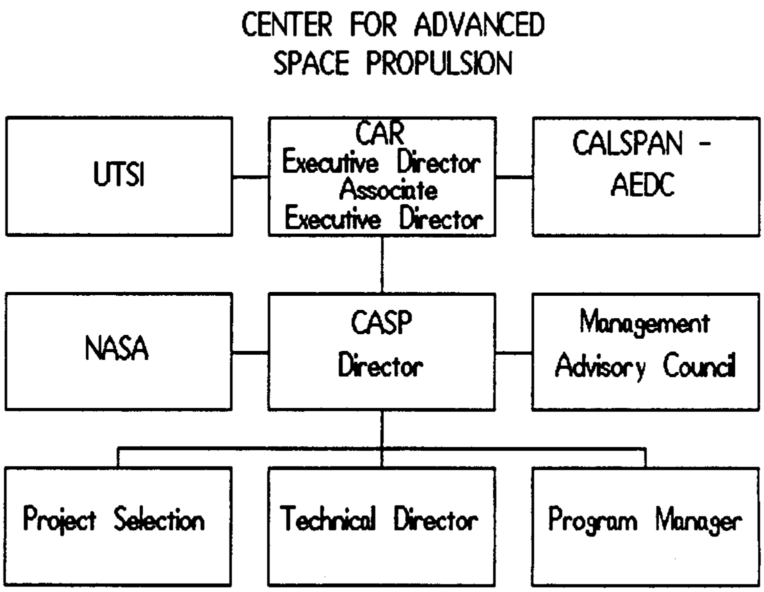

FIGURE 2.1

CASP has a small, full-time dedicated staff which includes the Director, a Technical Director, Program Manager, and Principal Secretary. Providing the continuity for project and facility planning, a Director for Project Selection is furnished on a part time basis from Arvin/Calspan.

CASP's Director has the overall responsibility for operating the organization in accordance with the NASA grant and within the broad policy guidelines established by the CAR Executive Director. The responsibilities of the CASP Director include establishing viable partnerships with industry and other universities, implementing the NASA grant requirements, project selection and direction, chairing the Management Advisory Council, and administration and financial management of CASP. CASP's Director is the primary interface with the NASA Office of Commercial Programs and with the Marshall Space Flight Center, the sponsoring field center, on matters associated with the Centers for the Commercial Development of Space.

Coordination of PI and research assistant activity, monitoring technical issues, defining new industrial opportunities, and assuring that industrial commercialization goals are met are the responsibilities of the Technical Director. In carrying out these tasks, the Technical Director assures adequate integration within the CASP program with respect to project plans, budgets and industrial participation.

CASP's Program Manager is responsible for defining Management Information System outputs which satisfy project cost tracking needs, defining and preparing budgets and financial projections for NASA and CAR, monitoring project costs, and implementing all administrative requirements associated with the NASA grant. As the primary project control interface with the industrial partners and universities, the Program Manager defines and coordinates the required formal agreements.

2.2 STAFFING

All individuals expending efforts in support of CASP projects are employees of either Calspan, the University, or a contributing industrial or university partner. Each individual reports functionally to the appropriate CASP management level for only those projects and/or activities that are supported by CASP while remaining at all times administratively attached to the home organization.

As of the end of the first year, all CASP permanent positions were filled and approximately twenty-one Staff, PI's, and research assistants supported the active projects. Dr. Fred Speer, the CASP Director, is the UTSI staff member who actively plans, directs, and controls CASP activity on a full-time basis. Marketing type activities consume at least 40% of his time while a considerable amount of the remainder is spent conferring with current industrial partners on the commercial application of existing projects as well as with NASA in periodic working sessions. Presentations to technical symposia and other NASA Centers have proven to have a high payoff in the first year structuring of a developing CCDS.

Dr. George Garrison, Professor of Mechanical and Industrial Engineering at UTSI, serves as the CASP Technical Director (40%), expends another 20% of his time on CASP marketing, and is the Principal Investigator for CASP's Magnetic Annular Arc (MAARC) project. Dr. Garrison continues to maintain a course workload at UTSI along with his CASP responsibilities.

Mr. Jim Johnson, Branch Manager at Calspan-AEDC Division is head of the Project Selection Office which consumes approximately 10% of his time. Additionally, Mr. Johnson interfaces with the appropriate AEDC managers for test requirements coordination.

Mr. Joseph Pawlick is a full time CASP/UTSI employee. As the CASP Program Manager he is the primary business interface with the CAR Business Administrator, UTSI, and our industrial partners. While the Program Manager expends some marketing effort, primary responsibilities center in the CASP administration area.

Mrs. Paula Reed is a full time CASP/UTSI employee who accomplishes all secretarial functions and assists both CAR and CASP with office administration.

2.3 FACILITIES

The Center for Advanced Space Propulsion is headquartered at The University of Tennessee Space Institute (UTSI) near Tullahoma, Tennessee, where it can utilize the facilities at UTSI and have access to the facilities at the U.S. Air Force's Arnold Engineering Development Center (AEDC) and the NASA Marshall Space Flight Center (MSFC) in nearby Huntsville, Alabama.

At the beginning of the period, CASP's personnel were housed at UTSI. As a temporary measure CAR rented approximately 2500 sq. ft. of existing office space in the UTSI Research Park. CAR, CASP, and CSE assumed occupancy of the rented space on February 1, 1988, and are currently operating from that location. The interim facility is fully equipped for all office work, conferences, and accommodates approximately 10 researchers in addition to the CAR and CASP staff. Terminals connected to UTSI computers were installed and access to the MSFC CRAY computer is being provided through a switch at the UTSI computer center. Forecast growth of the CASP indicates the existing rented office space will be adequate to satisfy requirements until construction of a new office and laboratory is completed.

The State of Tennessee and the Appalachian Region Commission (ARC) will jointly provide funding to construct a new facility for CASP. In December 1987, a formal application for ARC funding was submitted through the Tennessee Technology Foundation, a not-for-profit organization established to promote high technology development in Tennessee. The application proposed construction of a 9,520 sq. ft. building at an estimated cost of $863,000. The ARC was requested to provide $500,000 of the funding and the State of Tennessee, Department of Economic and Community Development (ECD) has agreed to provide the remaining $363,000.

In June 1988, ECD provided initial funding and authorization to proceed with the Architect-Engineer (AE) selection. A Building Committee was formed consisting of CAR, UTSI, CASP, UTK and TVAR representatives to solidify facility requirements (including site selection). The Committee selected an AE, executed a design contract, and is working with the AE in preparation of design plans and specifications.

CASP's anticipated accommodations include office space for forty-one investigators and staff, rooms for experiment build-up, and a computer center, including the data display (printers and plotters) area. In addition, a lab area to be used primarily for cold flow experiments (using sub-scale models) of propulsion systems or components will be included in the building.

Construction is targeted for FY89 at a site which overlooks Woods Reservoir, directly across the Rollins Creek Causeway from UTSI. Occupancy of the 9500+ square foot building is scheduled to begin in mid FY90.

2.4 GRANT ADMINISTRATION

The University of Tennessee-Calspan Center for Aerospace Research (CAR) received a 5-year grant (funded on an annual basis) beginning October 1, 1987 to establish a Center for Advanced Space Propulsion (CASP). CAR is a not-for-profit organization established to conduct basic and applied research in engineering and the physical sciences. CAR is co-located with CASP in the UTSI Research Park and is directed by Dr. E. M. Kraft (Calspan), Executive Director, and Dr. K. E. Harwell, Associate Executive Director and Dean of UTSI.

CASP's Director, Dr. F. A. Speer is responsible for conducting the Center's commercialization mission. As CAR's technical and financial interface with NASA for day to day operations, he structures CASP's marketing, budgeting, and cost tracking efforts to match commercialization goals. As Chairman of CASP's Advisory Council Dr. Speer receives feedback from the industrial partners relating to future opportunities and technology thrusts.

2.5 MARKETING

From its inception, CASP's management developed an aggressive marketing strategy focused on those particular areas where the experienced UTSI and Calspan investigators, backed by access to the nation's largest and most sophisticated test facilities could contribute significantly to the commercialization task. The initial five projects were aimed at specific goals, all of which were oriented toward four core areas:

Electric Propulsion
Cryogenic Fluid Transfer in Microgravity
Expert Systems Application
Advanced Chemical Propulsion

Some first year projects were undertaken to advance our knowledge and abilities in areas which appear to have a long term payoff. Investigations into Nuclear Propulsion and Rocket Fuels processing are examples of such projects.

Conversely, an investigation by CASP and MicroCraft into preparation of Rocket Engine Specifications proved that, while such standards are probably needed within the industry, the leadership to successfully bring the task to fruition would require resources which were not in concert with our commercialization goals.

An investigation of Expert Systems' application to manufacturing processes with the Saturn Corporation failed to reach the project stage. However, this endeavor assisted personnel who were initiating projects in Expert Systems to become intimately familiar with the industrial approach to product specifications.

Genesis of these potential projects were the result of the aggressive marketing approach taken by CASP. Personal contacts with industry and NASA leaders in the propulsion field, presentations at National and regional Symposia, and attendance at trade meetings were utilized to increase the number of joint projects with current partners and to identify potential new industrial partners. Satisfactory progress was made on both initiatives.

Beginning the year with five projects, CASP's marketing efforts paid off: Seventeen projects are in various stages of negotiation or completion at the end of the first year's effort. Of these, three will be accomplished in conjunction with two new industrial partners, while we will join with Marshall Spaceflight Center in joint investigations on two other projects which could lead to marketable products.

CASP's management is intent on continuing a strong, dynamic marketing program as an adjunct to the outstanding technical skills we offer to industry. In the end, CASP's success will be dependent on the strong ties established with its industrial partners in the propulsion community, and the mutual ability to assist NASA in the commercialization of space.

2.6 COMMUNICATIONS

Recognizing the need to disseminate program and project information to managers at NASA, CAR, our industrial partners and other decision makers, CASP instituted a number of paths for internal and external communications including briefings, coordination meetings, and a multi tiered series of reports.

Beginning with weekly staff meetings, face to face project and Center reviews are a key ingredient of CASP's comprehensive approach to facilitate the upward and downward flow of information. Monthly meetings with the key Center for Aerospace Research managers, Project Investigator coordination meetings (held on an as-required basis) ,and semi-annual conferences with the CASP Advisory Board are vehicles used to identify and disseminate current status or changing project information. Through the use of these periodic meetings all levels of the CASP information chain are kept current on the salient aspects of commercial developments.

Against a back-drop of coordination through focused meetings, a series of reports document those important aspects of CASP's development and project advancements. Monthly Executive summaries provide Project Investigators and CAR management with a running account of center activity and include monthly Management Information System reports. Highlights of these are merged with updated project status and published as quarterly reports. Disseminated to our Industrial Partners and the CAR Board of Directors, quarterly reports are a primary source of project status during the year. They also serve as invoice back-up for the service agreements we have reached with our industrial partners.

Service agreements with our industrial partners have been chosen as the appropriate manner to define the terms of our fixed price commercialization efforts. In each task statement, the partner defines the specific cost, schedule, and deliverables for the project. This clear definition of tasking is accompanied by reporting requirements which CASP is to meet. Generally, quarterly reports are used to define reporting milestones and are identified as deliverables. Through this approach, CASP management, our PIs, and those of our partners are kept aware of continuing progress.

2.7 INDUSTRIAL PARTNERSHIPS

To accomplish its mission, CASP must effectively join resources with industrial partners. Partnerships are driven by a mutual desire to develop projects and programs that have a commercial product or service as the ultimate goal. While actual commercialization might be projected as occurring either in the near term or farther into the future, it is axiomatic that all projects must have a clearly defined path leading to a commercial product, copyright or patent. Data and Patent protection features, unique to CCDS Grants, provide protection to the partners' intellectual rights for up to seven years. Recognizing the benefits of cost sharing, access to outstanding test facilities and Space Shuttle flight opportunities, many organizations find partnerships with CASP to be attractive.

Industrial participation may take the form of contributions of investigator man-hours, computer codes, test materials or test articles, or contracts for CASP researchers to accomplish specific tasks. CASP's industrial partners at the end of the fiscal year and their respective representatives on the advisory council are listed in Figure 2.7.1.

2.8 MANAGEMENT ADVISORY COUNCIL MEETINGS

Chaired by the CASP Director, the Management Advisory Council is comprised of representatives from the industrial partners and leaders in the CASP commercialization effort. Figure 2.7.1 lists the Advisory Councils' membership.

MANAGEMENT ADVISORY COUNCIL MEMBERSHIP

ORGANIZATION		REPRESENTATIVE
CASP	(Chairman)	Dr. Fred Speer
BOEING AEROSPACE		Dr. Mike Smith
ROCKETDYNE		Mr. Bill Ezell
TECHNION		Dr. John Teem
CALSPAN		Mr. Jim Johnson
SYMBOLICS		Mr. Howard Shrobe
UTSI		Dr. Dwayne McCay
MSFC		Dr. John McCarty
CASP		Dr. George Garrison

Figure 2.7.1

During FY 1988, two Advisory Council Meetings were held, the first at MSFC on December 10, 1987 and the second at UTSI on September 8, 1988.

Organizational topics were highlighted at the first meeting and included Advisory Council membership requirements, title to equipment, identification of the "end-product" during project selection, and suggestions on added topics which might lend themselves to CASP project investigations. The council was highly supportive of CASP and the role it might take in the application of propulsion system research to industrial needs. It was decided that the Council would meet twice each year and the meetings would be hosted by succeeding Council Members.

Project and marketing performance were highlighted at the second meeting on September 8, 1988 at UTSI.

The following comments and observations were provided by the Advisory Council:

1) CASP's first year's activities are considered to be successful and show that it is headed in the right direction;

2) CASP's long term strategy must define core capabilities where it can become an acknowledged expert. CASP must emphasize and be active in its strengths;

3) Computational Fluid Dynamics, Artificial Intelligence, Electric Propulsion and Microgravity Fluid Management appear to be the strengths of CASP at this point in time. Strategy should be to develop self-sufficiency in these areas.

4) Fluid Management in space is burdened with a large number of unknowns and yet cryogenic fluid transfer is an integral part of all long duration missions and Space Station operations;

5) With foreign launch services available, CASP's future is probably best not tied to development of new, large rocket motor systems;

6) CASP must keep the potential customers in focus; will industry invest in CASP projects if there is little or no payoff?

7) Pick the "tent poles" of the marketing effort. What are the specific products CASP wants to market? In defining the target market has CASP identified those areas where a unique service will be offered to commercial endeavors. Can CASP provide it better or more economical than anyone else?

8) CASP's projects and workload must be compartmentalized so that competing, sensitive projects can be worked without jeopardizing industrial relationships;

9) CASP's major long term goal is survival. The strategy must clearly display the path by which self sufficiency can be achieved.

III. FINANCIAL

3.1 FINANCIAL PLAN

CASP's financial goal is to become self-sustaining independent of the NASA grant within five (5) years. To extend CASP's existence beyond the life of the grant demands fiscal planning which blends contracts with industrial partners and NASA centers, contributions of equipment or codes, and other assets into a coherent financial plan. A six year CASP financial model was developed to describe the financial components of CASP's future and is shown in Figure 3.1. Contracts, in-kind contributions, and the Grant are all shown as the primary constituents of income.

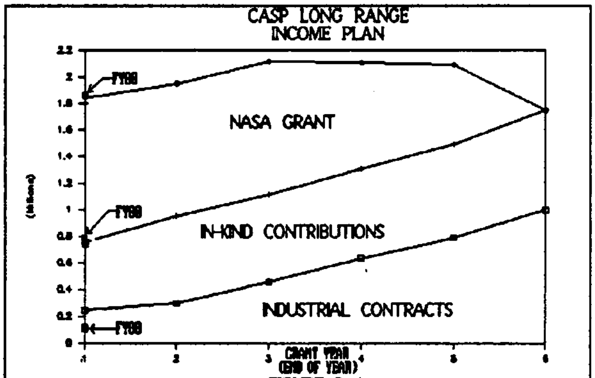

FIGURE 3. 1

Marked on the Y-axis are the actual sources of income experienced during the first year. Note that, while industrial contributions and contracts are somewhat lower than anticipated, in-kind contributions are greater than expected. Total of the two closely matches the goal; however, the mix does not.

Heightened attention by our industrial partners to FY 88 service agreements resulted in an upswing of invoices being approved at years' end. Payments for completed work on our existing fixed-price contracts will continue to be received as financial departments honor our invoices. However, the early conversion of UTSI and Calspan cash contributions to in-kind contributions resulted in a short-fall of cash and contracts.

While CASP was successful in obtaining the five year Grant to establish a CCDS in October, the first letter of credit was not received until February, 1988. CASP was funded only for the first half-year and a subsequent round of budget and funding discussions led to the second half funding being received at CASP in July.

Thus, in summary, CASP's financial objectives for the first year were virtually achieved. A foundation of good rapport with our industrial partners and CASP marketing successes start the second year on a solid footing.

3.2 REVIEW OF FY 88 ACTUAL VS BUDGETED COSTS

Figure 3.2.1 displays the actual CASP costs accrued during FY88 compared to the budget for the four major cost categories -labor, travel, materials, and overhead. Minimal variances in labor, materials, and travel are evident in this figure which shows actual costs before re-programming. These variances were dealt with in an end of the year re-programming action by the CASP Director.

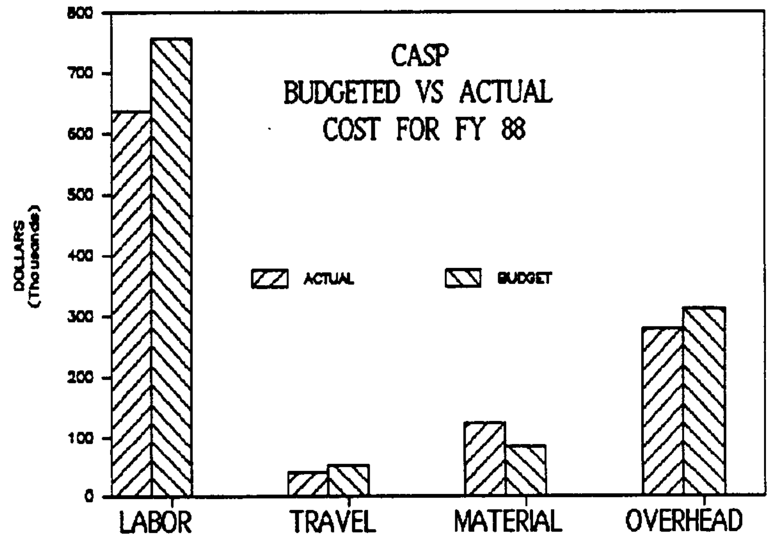

FIGURE 3. 2. 1

Variance in labor resulted from delays in contract initiation with our industrial partners and late arrival of the first letter of credit. Both causes impacted the start of our initial projects to some degree. As the project pace increased in the latter part of the second period, monthly labor costs approached the plan.

Materials to support an added ground test in the Liquid Cryogen Transfer in Microgravity project and the need for increased microprocessor capability to support an expanded Expert Systems and CFD workload caused materials cost to increase in the second half of the FY. In each case it was necessary to expend FY88 material funds to meet project technical objectives.

Project travel closely matched the forecast and was heavily front-end loaded to meet the demands of the emerging workload.

CASP's overhead is set at 35% by CAR. A slight variance in the overhead account results from any under/overrun of the major CASP categories.

3.3 CASH AND IN-KIND CONTRIBUTIONS

CASP's proposal defined contributions to the center as either cash or contributions in lieu of cash. The latter, termed "in-kind" may consist of industrial participants' salary, furniture, equipment, computer codes, microprocessors, test article fabrication, computer use charges, etc. In either case CASP applies these resources to meet Center and project milestones.

3.3.1 Cash Contributions

Through the end of FY 1988 UTSI has made cash contributions totaling $19,278. This contribution paid salaries for UTSI personnel which were accrued during the period of 1 October '87 until grant funding was received. Funding from Auburn and MSFC for the Space Power Expert System project was not received as anticipated since a contract between UTSI and Auburn pre-empted CASP's effort. An anticipated first year contribution by CALSPAN was clarified into a commitment to provide that amount during the five year grant period, as the need arises. Invoices for $100,000 were submitted to industry for the contracts supported by CASP.

3.3.2 In-Kind Contributions

Industrial, University, and NASA-MFSC in-kind contributions have totaled $653,975 for the year. Examples include: a Symbolics computer for Expert Systems development, Principal Investigator salaries, computer use charges at MSFC, overhead recovery at UTSI, purchasing and corporate support, furniture, and computer codes. Air Force, NASA, and private industry funds were used to develop and modify the PARC2D code, which is used to model nozzle and combustor flowfield dynamics. The PARC2D code was contributed to CASP by AEDC and is being used to model complex flowfields within high area ratio nozzles, and the Magnetic Annular Arc thruster. Development of this code required several man years of effort and is considered to be a major tool for CASP's future projects in the CFD area. A contribution of CRAY usage charges from NASA MSFC has aided two of our project investigations considerably as has the KIVA code provided by Rocketdyne.

3.4 FINANCIAL PERFORMANCE INDICATORS

CASP's grant defines first year performance goals for the CCDS. Additionally, the proposal which established CASP identifies other yardsticks by which CASP's effectiveness can be rated. CASP's financial performance during the start-up period was very positive.

In his grant letter, Jay M. Berman, NASA Grants Specialist defined CASP's cost sharing goals (percentages of total income) as: 64% NASA, 10% In-Kind, and 26% other support. Figure 3.3.1 depicts the CASP performance and comparison with the goals and shows the impact of the larger than anticipated level of in-kind contributions on the cost sharing percentages.

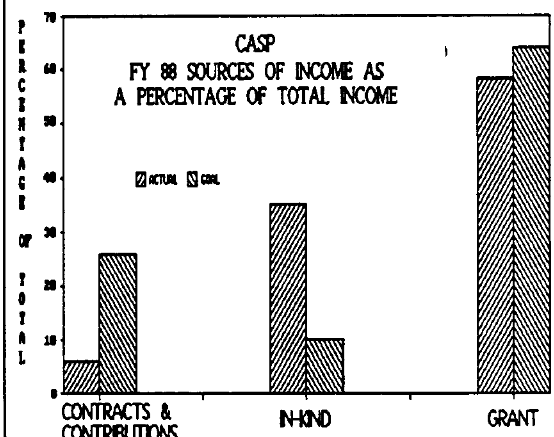

FIGURE 3. 3. 1

Indicators which were included in the proposal for CASP summarize the effect of leveraging which the center would use to attract potential partners. Leveraging occurs when CASP shares the cost of a project with a partner. The ratio of Total funding to NASA grant funding was proposed to be 2.35. Our actual percentage in FY 88 was less (1.71). A target of 135% was set for Non-NASA to NASA funding and our experience was 71%. In each case our inability to completely capture industrial contracts, a high initial cost share ratio with our industrial partners, and lower than anticipated University/Calspan cash contributions were the drivers. A greater testing role for AEDC was anticipated in the proposal. A lack of projects requiring the sophisticated facilities which allow AEDC to be cost effective, lowered our projections and reduced the actual in-kind contributions. CASP's marketing thrust for FY 89 has fully recognized the need for greater cost share percentages with our industrial partners and the timely accrual of cash and in-kind contributions.

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IV. TECHNICAL DISCUSSION

During the year seven projects were initiated and funded as follows:

Magnetic Annular Arc Thruster
SSME Fault and Diagnosis Expert System
Liquid Cryogen Transfer & Storage in Low Gravity
Spray Combustion Stability
Advanced High Area Ratio Nozzle
Component Life Management Expert System
Ion Propulsion

Work is proceeding in all of the above projects except the last. The Ion Propulsion project has been temporarily discontinued until new tasks can be defined and negotiated with the industrial sponsor. An anticipated contract in this area did not materialize.

A year end status report on each of the projects follows.

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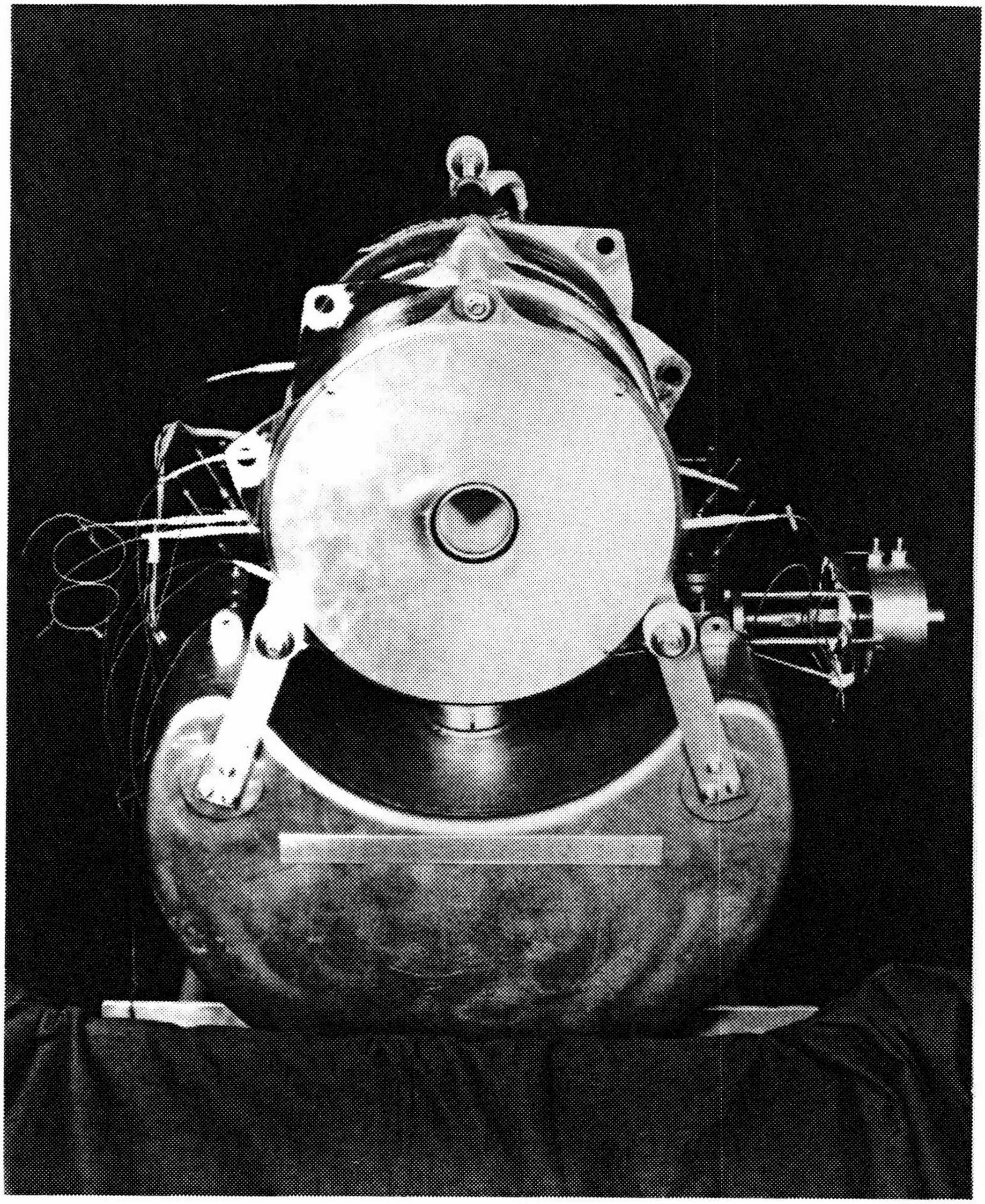


MAGNETIC ANNULAR ARC (MAARC) THRUSTER

SECTION 4.1

4.1 MAGNETIC ANNULAR ARC (MAARC) THRUSTER

4.1.1. Principal Investigators:

DR. GORDON CANN, TECHNION, INC.
DR. GEORGE GARRISON, CASP/UTSI

Other Investigators:

MR. HERBERT THOMAS, CASP/UTSI GRA

4.1.2 Objective:

Design and build a MAARC thruster and demonstrate reliability and performance for comparison with other electric thruster types.

The commercial product is a thruster that will have potential applications for deep space missions, for orbital transfer and possibly for station keeping.

4.1.3 Approach:

A nominal 25kw MAARC thruster will be designed and built at Technion, and tested in a vacuum chamber at the Lewis Research Center or at AEDC. The thruster specifications are as follows:

Power:	20 - 30 kw
Thrust:	0.75 - 1.25 Newtons
Specific Impulse:	1500 - 2500 sec
System Thrust Efficiency:	30 - 40%
Propellant:	Nitrogen/Hydrogen/Ammonia

It is expected that the design, fabrication and testing of the thruster will be completed during FY89.

4.1.4 Accomplishments in FY88

4.1.4.-1 Thruster Hardware:

Figure 4.1-1 depicts the basic components and configuration of the thruster. The discharge is initiated by thermionic emission from the conical tip of the tungsten cathode (part 6 on figure) with the buffer electrode (21) serving as the anode. The arc is then transferred to the accelerator anode (25) and the magnet (28) is excited. Gas is injected through both the electrode assembly (22) and the anode assembly (26). The magnet coils can be electrically in series with the arc or can be powered separately.

One significant advantage of a MAARC type thruster (Ref. 1,2) over other electric thrusters is that it can produce high specific impulse values (1550-5000 sec.) at reasonable thrust efficiencies (40-50%) with most non-oxidizing propellants. Potential propellants can include:

a) All of the noble gases
b) All of the alkali metals
c) Most of the standard rocket propellants, e.g.:
   hydrazine
   ammonia
   hydrocarbons
d) Other gases, e.g., nitrogen and hydrogen

In the past, vacuum pumping constraints have limited the propellants that can be tested in the laboratory to mixtures of the alkali metals and hydrogen and/or nitrogen. The latter two were injected through the cathode-buffer system to generate the "virtual" cathode jet or upstream cathode jet. Obviously, ammonia could have been used. If cryo-pumping is required, cost considerations dictate that for the initial ground tests in this program, nitrogen should be used for the propellant. For the first space test, ammonia would appear to be a promising propellant.

Preliminary design of all components of a MAARC ground test article has been completed at Technion. A schematic of the engine mounted on the Technion thrust stand is shown in Figure 4.2-2. Detailed design has been completed for two configurations of cathode-buffer subassemblies, as well as for the water-cooled magnet coils. The magnets have been fabricated, operated and calibrated. Preliminary tests have been conducted at Technion on the cathode-buffer assemblies.

The larger of the two cathode-buffer configurations has been selected for fabrication because:

a) It is important to determine the optimum ratio of gas flow between the cathode-buffer and the anode. The selected cathode-buffer design permits adjustment of the ratio over a wide range. Once the ratio is established, the appropriate arc length and orifice diameter can be incorporated into the small unit for establishing optimum performance.

b) It may be desirable to have an alternate mode of operation where the engine can be operated as an arcjet (high thrust, Isp <1,000 sec.). This can be accomplished by retracting the cathode and injecting most, if not all, of the propellant through the cathode-buffer combination.

4.1.4.-2 Theoretical Model

The complex physical and gasdynamic processes within any rocket propulsion device utilizing electromagnetic acceleration prohibit the use of simple theoretical models for performance prediction. Recently, two-dimensional computer models have been developed to describe the basic phenomenon in plasma thrusters with and without an applied magnetic field. Tanaka and Kamura (3) analyzed a two-dimensional electromagnetic field and a quasi-one-dimensional plasma flow with an externally applied magnetic field. Park and Choi (4) studied a two-dimensional plasma flow and a two-dimensional electromagnetic field with the only component of the magnetic field assumed to be in azimuthal direction. Chanty and Martinez-Sanchez (5) solved a two-dimensional thruster flow having an induced magnetic field and considered a fully ionized, isothermal plasma.

Since the applied magnetic field in a MAARC-device induces a velocity-component in the azimuthal direction, it is important to include the azimuthal momentum equation in the equation set to be solved. Currents occur naturally in the axial-and radial direction. Due to the Hall effect, currents can arise in the azimuthal direction as well. A realistic applied magnetic field has components in the axial and radial direction while the strongest induced magnetic field will be in the azimuthal direction. Hence, it is important to include all components of the magnetic field and the current densities in the analysis.

A full solution of the Navier-Stokes equations can be obtained with the PARC-code, developed by Pulliam and Steger (6). This code uses a fully implicit algorithm to solve the Navier-Stokes equations in a strong conservative form. The time dependence of the flow properties is utilized as an iteration mechanism to obtain a steady-state solution. The robustness of the fully implicit code and the similarity of the Navier-Stokes equations to Maxwell's equations as well as its capability to perform on complicated geometries made the PARC-code a desirable source-code.

Since only a two-dimensional version of the PARC-code was available, the azimuthal momentum equation was introduced and tested for simple cases. Maxwell's equations were transformed to a strong conservative form and a coordinate transformation of those equations was performed. The resulting equations for the non-dimensionalized variables are:

$$\frac{\partial}{\partial t}\left[j^{-1}\begin{pmatrix} B_{i_x} \\ B_{i_y} \\ B_{i_z} \\ E_x \\ E_y \\ E_z \end{pmatrix}\right] + \frac{\partial}{\partial \xi}\left[j^{-1}\begin{pmatrix} \xi_y E_z \\ -\xi_x E_z \\ \xi_x E_y - \xi_y E_x \\ -\xi_y B_{i_z} \\ \xi_x B_{i_z} \\ -\xi_x B_{i_y} + \xi_y B_{i_x} \end{pmatrix}\right] + \frac{\partial}{\partial \eta}\left[j^{-1}\begin{pmatrix} \eta_y E_z \\ -\eta_x E_z \\ \eta_x E_y - \eta_y E_x \\ -\eta_y B_{i_z} \\ \eta_x B_{i_z} \\ -\eta_x B_{i_y} + \eta_y B_{i_x} \end{pmatrix}\right] = j^{-1}\begin{bmatrix} 0 \\ 0 \\ 0 \\ \frac{-4\pi}{c} j_x \\ \frac{-4\pi}{c} j_y \\ \frac{-4\pi}{c} j_z \end{bmatrix}$$

Where the corrections for the axisymmetric version are not included.

In order to use the same algorithm, the Euler backward differencing:

$$\Delta \hat{Q}^n + \Delta t^n \left(\frac{\partial \hat{F}_j^{n+1}}{\partial \xi_j}\right) = \Delta t (RHS)^n$$

with

$$\hat{F}_j^{n+1} = \hat{F}_j^n + \frac{\partial \hat{F}_j^n}{\partial \hat{Q}^n} \Delta \hat{Q}^n$$

was applied to Maxwell's equations. Also, the same approximate factorization

$$(I + \Delta t \frac{\partial}{\partial \xi} A_1)\,(I + \Delta t \frac{\partial}{\partial \eta} A_2) \Delta \hat{Q}^n = \Delta t (RHS)^n$$

and a reasonable artificial "viscosity" was introduced. Uncoupling of the equations in the original form is impossible, since the matrices A_1 and A_2 are singular. However, deleting the axial or radial direction from those equations establishes non-singular matrices, that can easily be diagonalized. The diagonalized form of the factored algorithm is then

$$T_1(I + \Delta t \frac{\partial}{\partial \xi} \Omega_1) N_{12} (I + \Delta t \frac{\partial}{\partial \eta} \Omega_2) T_2^{-1} \Delta \hat{Q}^n = \Delta t (RHS)^n$$

with

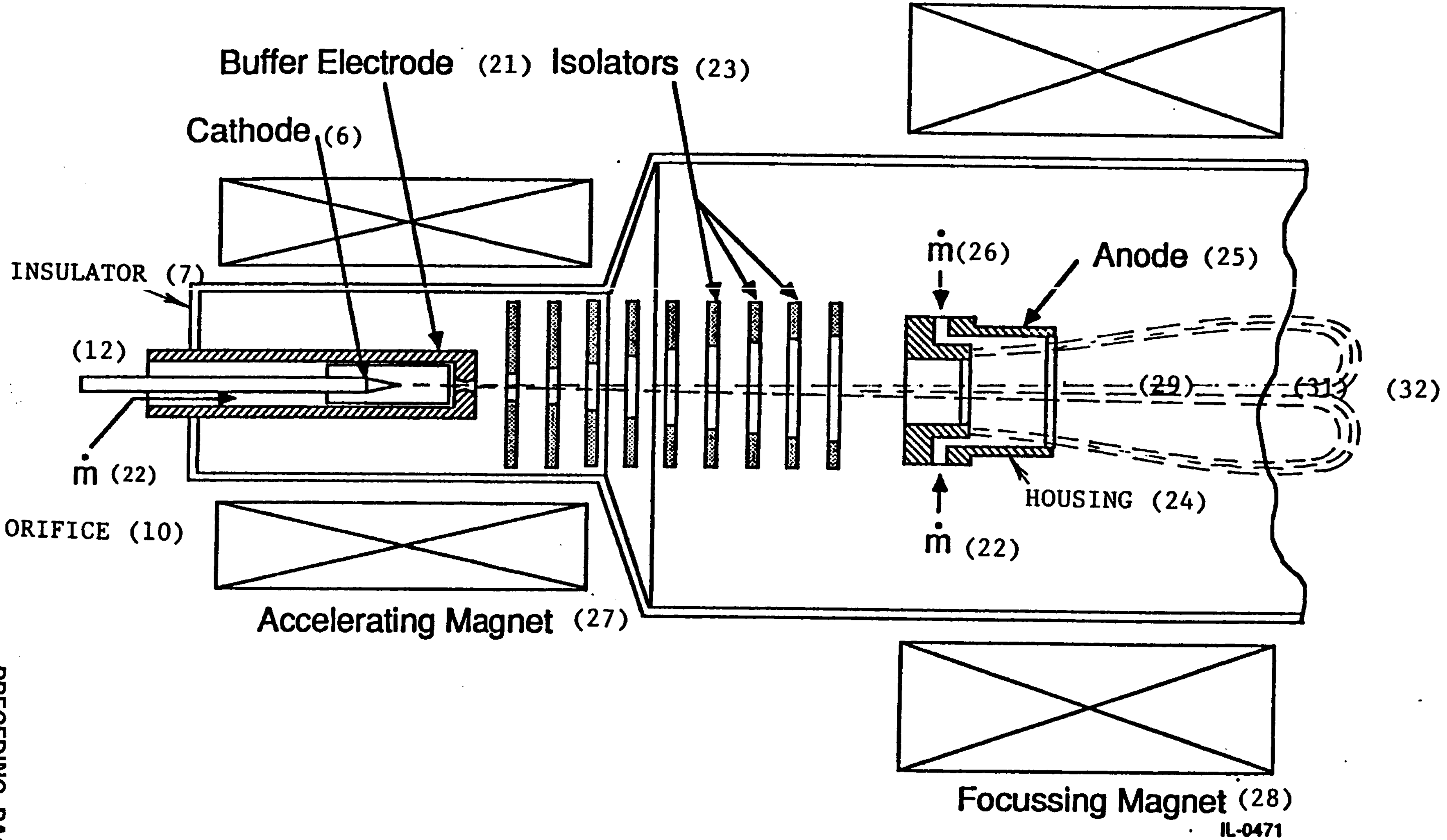
$T \hat{=}$ eigenvector matrices

$N_{12} = I$ (the identity matrix)

$\Omega = \pm \xi_x; \ \pm \xi_y; \ \pm \eta_x; \ \pm \eta_y$

with Ω depending on what direction is included in the matrices A. The eigenvalues provide a complete set of linearly independent eigenvectors. The appropriate changes were done on the original PARC-code and the resulting code was verified on a simple problem (a homogeneous electric field in the Y-direction). Convergence problems occurred, when the x-direction was included in the matrix, instead of the y-direction. Therefore, the program was modified, such that both the x-and y-direction could be included in the matrix and the user has an option of how many iterations are performed including the y-direction, before one iteration is performed including the x-direction.

Verification of the program with more complex problems has not yet been accomplished. Appropriate boundary conditions need to be defined and implemented in the code in order to complete this task.



MAARC SCHEMATIC

FIGURE 4.1-1

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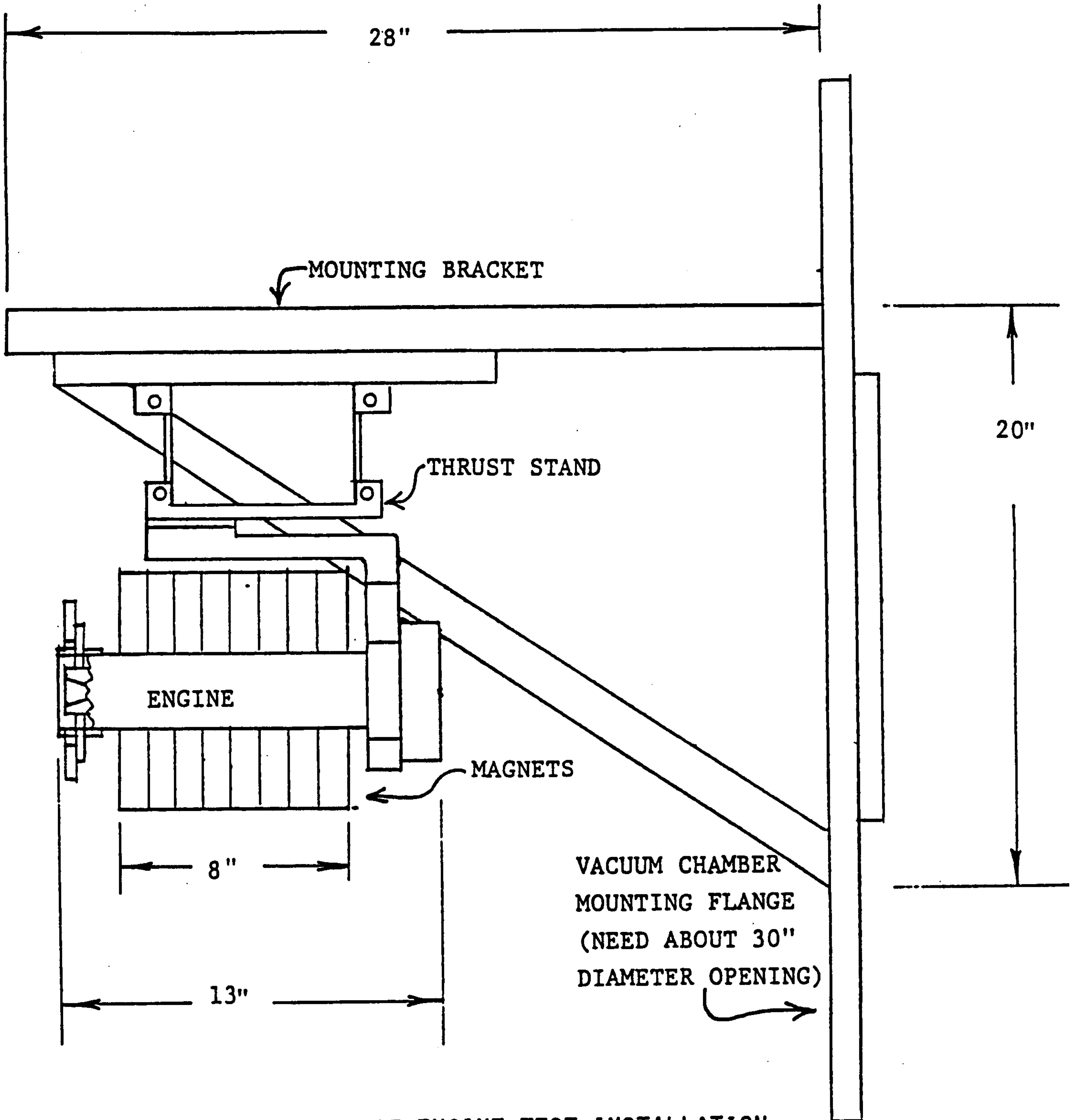

SCHEMATIC OF ENGINE TEST INSTALLATION

FIGURE 4.1-2

4.2 SSME FAULT MONITORING AND DIAGNOSIS EXPERT SYSTEM

4.2.1 Principal Investigators:

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DR. MOONIS ALI, CASP/UTSI

Other Investigators:

MR. U. K. GUPTA, CASP/UTSI GRA
MR. E. L. KIECH, CASP/CALSPAN
MR. W. E. DIETZ, CASP/CALSPAN

4.2.2 Objective:

To develop diagnostic methodologies applicable to real-time fault detection and diagnosis during SSME ground testing.

The commercial product will be a prototype expert system software that can provide fast response fault detection and warning of out-of-range operating conditions.

4.2.3 Approach:

The purpose of this project is to design and develop an expert system for automatic learning, detection, verification and correction of anomalous propulsion system operations in real time. Although identification of intelligent techniques and tools for providing system reliability have been reported for simple mechanisms, the use of such techniques in real-life complex systems has not yet been accomplished. In the past, attempts have been made to achieve reliability for identifying system-level failures by employing techniques, such as massive redundancy with voting and error-detecting codes. However, these techniques have been unable to yield the high level of reliability required even in simple mechanisms without a tremendous amount of hardware overhead and/or performance degradation.

The understanding of the functional requirement and complexity of a rocket engine control system, which contains an integrated status monitoring system, can be greatly assisted by a complete description of the system component interactions. Large, high thrust liquid rocket engines require a turbo pump system to inject high pressure propellants to the thrust chamber. The hot gases for driving the turbopump may be produced by precombustion in a gas generator or from regenerative heating in the thrust chamber coolant system. The main function of the rocket engine control system is to control the propellants' (fuel and oxidizer) flow into the turbopump pre-burners and into the main combustion chamber injectors. Complex, time dependent, propellant flows are required during engine start, throttling, and shut down because of thermal heating and combustion stability constraints.

Improved operability and reliability can be achieved in a liquid rocket engine with advanced sensors, instrumentation and expert logic combined into a monitoring system which actively participates with the control system. The benefits of combining an intelligent monitoring system with an active/adaptive control system include both improved performance and improved reliability (system safety). However, the reliability of the advanced monitoring and control system must be much greater than the mechanical systems of the rocket engine for these benefits to be realized.

Thus the system safety and reliability require the use of an expert system for aiding in diagnosing and recovering from faults. By exploiting large amounts of domain knowledge, expert systems are able to accurately assess information and determine the cause of a fault. An on-board expert system, then, would help the propulsion system's intelligent controller to focus on the sources of faults and increase the effectiveness of its attempts to correct them. However, we must also recognize that a majority of the rocket engine component failure modes will not be correctable by control system actions and will require immediate engine shutdown to prevent serious or catastrophic failure of the engine. In these situations the expert system will look for an alternative mechanism and its components' lifetimes to provide the needed support.

4.2.4 Accomplishments for FY88

The implementation of the expert system has been divided into several phases. Some of these phases have been completed and the work reported in the referenced publications which provide details and results of these implementations. For example, the work on engine behavior analysis, machine learning of the behavior, and modeling is reported in references [1-5]; research on modeling and employing design as well as deep-level domain knowledge has been performed successfully, and the results obtained so far have been reported in references [6-10]. However, we feel quite a bit more research needs to be done in this area, specifically related to propulsion in general and rocket engines in particular. Our present emphasis on this aspect is indicative of this need.

Two prototype SSME fault monitoring and diagnostic systems have been developed, one using basic AI/expert system concepts while the other draws from neural network concepts.

4.2.4-1. Expert System Model Integration:

Our current efforts in the expert system implementation are concentrated on integrating all the models of knowledge as well as the diagnostic process itself. The description of one of the many fault examples, which we are employing in our work, will put some light on our current research. We selected the Main Combustion Chamber (MCC) injector failure example for this purpose. This example is chosen because there exists a documented series of incidents involving this fault with adequate sensor data, and this fault exhibits a large interaction with other components' performance.

The thirteen sensors selected for diagnostic analysis are listed in Table 1. The locations of these sensors are shown on a flow schematic of the rocket engine components, illustrated in Figure 4.2-1. The behavioral data of the thirteen sensors is shown in Figure 4.2-2 for the time period ranging from the stabilized normal situation and the fault occurrence to the end of the fault. This sensor data illustrates a clearly marked trend during the failure event. Our trend analysis and machine learning program identified several parameter characteristics which are important in diagnosing this fault. These characteristics include sensor value slope variations and inter and intra sensor slope relationships, slope-magnitude relationships, temporal relationships, magnitude relationships, duration relationships, and magnitude-time relationships [3]. The machine learning program conceptualizes these characteristics. An example of one of several concepts formed for MCC injector failure is that "MCC Hot Gas Pressure" rises as oxygen leaks into the hot gas stream above the face plate, while delta pressure across both face plates drops due to plate erosion. The rise in "HPFT Discharge Temp" and "HPOT Discharge Temp" occurs when both mixture ratio and turbopump load change with the leak. The leak initiated pressure and temperature changes must be traced upstream to determine slope changes in the affected component.

The machine learning program employed in our system generalizes these concepts for multilevel representations. The lowest level representation includes all the details, but the highest level stores only abstract general concepts deduced from the low level details. The semantic net representation has been employed to represent these concepts. Figure 4.2-3 illustrates intersensor slope relationships among dominant sensors found to be significant by the machine learning program for MCC injector failure [3]. Each node in the network represents a dominant sensor. Each arc between sensor nodes denotes the type of relationship depicted by the relative behavior of these two sensors. The machine learning program determined a total of four types of slope relationships which could exist between any two sensor behaviors; these slope relationships are shown in Figure 4.2-4.

4.2.4-2. Neural Network-based Diagnostics:

We are also implementing neural network-based diagnostic systems for the Space Shuttle Main Engine (SSME). This effort aims to examine methods of employing the experimental data obtained from engine ground tests for the training and evaluation of a network-based diagnostic system.

The SSME has been extensively tested in ground-based facilities; some of these tests have resulted in the occurrence of several different types of fault conditions. The data from these tests were used as training sets for the SSME diagnostic system.

• Two types of experimental data were available. from SSME tests. The first type was experimental curves, representing the temporal behavior of various engine sensors during testing activities. The second type was summaries of curve features, which included 1) an "excursion interval", defined as the time from detection of a transient to the maximum deviation of a sensor value from the pre-transient level, and 2) an average rate of change of a sensor reading over the excursion interval. Twenty sensors were present on all tests in which a fault condition occurred. The sensors measured various engine parameters, such as main combustion chamber pressure, turbine discharge temperatures, turbine speeds, and valve positions.

In the first neural net prototype, investigations have been centered on 1) training the neural networks using noisy experimental data and 2) categorizing input patterns which represent curves similar to the training sets, but with varying noise intensities imposed. Because of limited experimental curve data, the neural networks using a binary input representation were trained with one example for each sensor. With this single training example the networks could reliably categorize input patterns exhibiting noise levels of up to 20 percent.

The second neural net prototype uses the curve feature data summaries as input. Since excursion intervals and average rates of change were available for all twenty parameters, a neural network was implemented with 40 inputs. The engine behavioral patterns for each fault were therefore represented as a vector of 40 real numbers.

Data summaries from 27 tests were available for training the neural networks. The 27 tests resulted in failure scenarios involving six main structural groupings within the SSME: 1) injectors, 2) controls, 3) duct manifold, and heat exchangers, 4) valves, 5) high pressure oxidizer turbopump, and 6) high pressure fuel turbopump.

A neural network topology was implemented which consisted of 27 output nodes, each identified with a specific test. A network implementation of this type is designed to identify the closest test scenario corresponding to an unknown input.

All 27 data summaries were used as training sets. Testing was done by presenting perturbed versions of the training sets to the networks, and examining which of the 27 test scenarios were activated. Perturbing the data summaries does not necessarily reflect the direct effects of instrument noise, but may include errors which occur extracting curve features. Many conventional feature extraction algorithms are highly susceptible to errors generated not only by noisy sensor data, but also by assumptions inherent in the feature extraction algorithms themselves. In all cases, the perturbed versions of the training sets were identified correctly up to perturbation levels of 30 percent.

4.2.5 Current Status

The prototypes of the diagnostic systems have been developed and trained using a small set of engine behavior examples representing about thirteen faults. The prototypes have been limited in their scope to a lesser degree of generality as well as to a small number of faults because of the lack of fault data. However, the response of these systems was good, in accuracy as well as in time, when they were presented with the unknown test data. The prototypes have been implemented on a Symbolics 3670 LISP machine, VAX 785 and on a personal computer. The results obtained so far have been very interesting and encouraging. Now we intend to enhance the capability and power of these systems as discussed in the next section.

4.2.6 Future Work

The problem addressed in our current research focuses on the automatic detection, verification and correction of anomalous propulsion system operations. The solution of this problem will increase the reliability of complex systems like the Rocket Engines. Our current research will lead to the solution which centers on the development of a reliable intelligent propulsion control and monitoring system whose functional component relationships are shown in Figure 4.2-5. The Propulsion System High Level Intelligent Controller (HLIC) is the communication and decision center for the propulsion system and interfaces with the flight vehicle control system which may also be an intelligent system. A set of sensors will monitor component performance and detect abnormalities which will then be validated with respect to varying engine dynamics and behavior. A further analysis of confirmed faults will be performed by the Diagnostic Expert System, which will employ domain knowledge as well as known characteristic engine behavior and will determine the root causes of the faults. The faulty engine status will be fed through the HLIC module to the flight vehicle control system which will determine the criticality of the situation. The HLIC (which has access to the control information) will use criticality and diagnostic information to determine corrections in control variables which could rectify faults. These corrections will be applied to actuators to improve the propulsion system's performance which is monitored through sensors. The resulting performance, engine dynamics and engine behavior will be analyzed by the diagnostic expert system, and the cycle will repeat until the abnormalities disappear. In case the abnormalities will be due to a faulty engine which cannot be corrected during the flight, a shut down command will be issued and analysis will be performed to estimate the load and component life of the remaining propulsion system. The results of this analysis will be fed to the control adapter which applies constraints on the control variables in order to maintain optimum performance and high probability of completing the flight with the remaining life of the propulsion system components.

The core of the reliable propulsion system is the diagnostic expert systems called "Integrated Expert Systems" (IES). The architecture of IES, shown in Figure 4.2-6, not only covers the fault diagnosis but also automatic knowledge acquisition. Since the manual acquisition of knowledge has been a bottleneck in developing an expert system, we propose its integration with the development of the diagnostic expert system.

We will integrate the engine behavioral diagnosis model with engine design as well as engine fault and repair history. The use of design knowledge will be significantly important in diagnosing faults. For example, the fuel and oxidizer preburners for the propellant turbopumps have an injector design very similar to the main combustion chamber injectors. Thus, failure of the preburner injectors will result in upstream and downstream flow changes in temperature and pressure with characteristics very similar to the MCC injector failures. However, knowledge of the design flow paths and component interconnections would allow an intelligent fault detection system to discriminate a preburner injector failure from the characterization of the MCC injector failures. Corresponding instrumentation in the fuel and oxidizer preburners measures faceplate delta-pressure and preburner combustion chamber pressure relative to fuel and oxidizer inlet pressure. Injector failure in the preburners will have a significant influence on mixture ratio and combustion temperature. HPOT and HPFT discharge gas temperature will reflect directly any changes in preburner mixture ratio, and would be a strong discriminator for locating the injector failure in either the MCC or preburner. Thus a fault which has not been experienced previously may be recognized and diagnosed.

An illustration of the use of fault and repair history in diagnosing faults is the turbopump bearings which are a critical component with a long history of failures. Excessive bearing wear is generally associated with vibration and increased temperature of the bearing. A trend toward increased vibration levels or increasing temperature is a strong indicator of remaining bearing life or time to failure. One other failure mode will exhibit excessive vibration. Turbine blade failure is characterized by the sudden onset of turbopump vibration and associated performance loss which should allow clear discrimination between bearing failure and blade failure. Thus, two sensors in combination with bearing failure history will provide an excellent predictor of failure.

The system functions include automatic knowledge acquisition, integrated knowledge base creation and maintenance, and fault diagnosis. We view the task of IES as a process of reasoning from behavior to design, or more precisely, from misbehavior to structural or design defects. The system will be presented with a rocket engine exhibiting some form of faulty behavior and it must infer the structural aberration that is producing it. The task is interesting and difficult because rocket engines are complex and because there is no well developed diagnosis theory. Our ultimate goal in designing and developing IES is to provide a level of performance comparable to that of an experienced engineer including: understanding and reasoning with the behavioral data; employing design knowledge and heuristic knowledge in the inference and diagnostic process; selecting and interpreting the results of input test patterns; and communicating with engineers in solving diagnostic problems.

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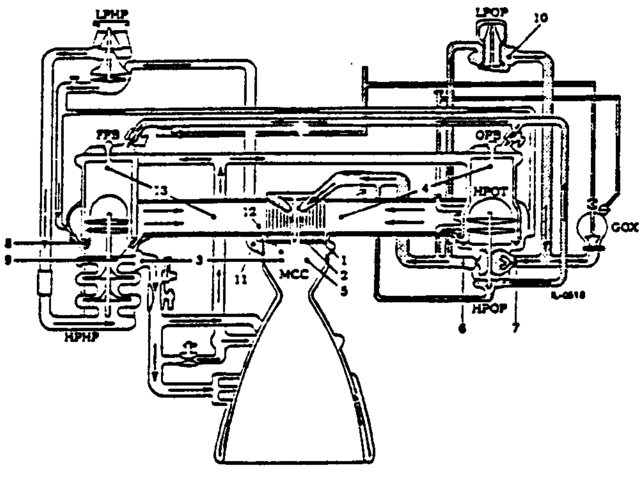
TABLE 1:
Sensors Selected for MCC Injector Failure Analyses

1. Secondary faceplate DELTA P. (SFP-DELP)
2. Primary faceplate DELTA P. (PFP-DELP)
3. High Pressure fuel pump discharge pressure minus main combustion chamber pressure (HPFPDP-MCC PC)
4. Oxygen pre-burner chamber pressure minus main combustion chamber hot gas inlet pressure (OPB PC-MCC HGIP)
5. Main combustion chamber pressure (MCC PC)
6. High pressure oxygen turbine discharge temp (HPOT DT1)
7. High pressure oxygen turbine discharge temp (HPOT DT2)
8. High pressure fuel turbine discharge temp (HPFT DT1)
9. High pressure fuel turbine discharge temp (HPFT DT2)
10. Low pressure oxygen pump discharge pressure (LPOP DP)
11. Main combustion chamber coolant discharge temp (MCC CL DT)
12. Hot gas injector DELTA P (HG INJ DELP)
13. Fuel pre-burner chamber pressure minus MCC hot gas inlet pressure (FPB PC-MCC HGIP)



Schematic of the Rocket Engine Components
Figure 4.2-1

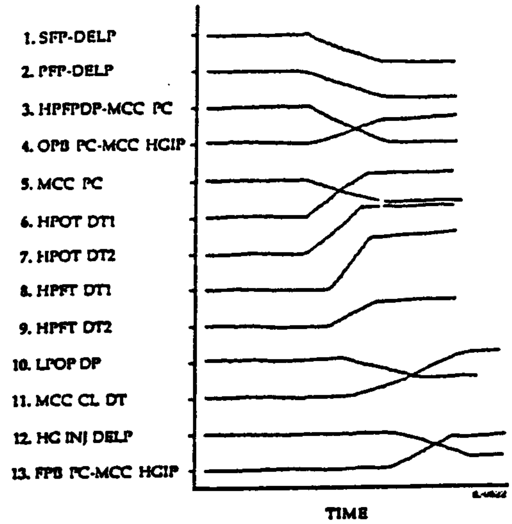


Figure 4.2-2 MCC Injector Failure (typical sensor data)

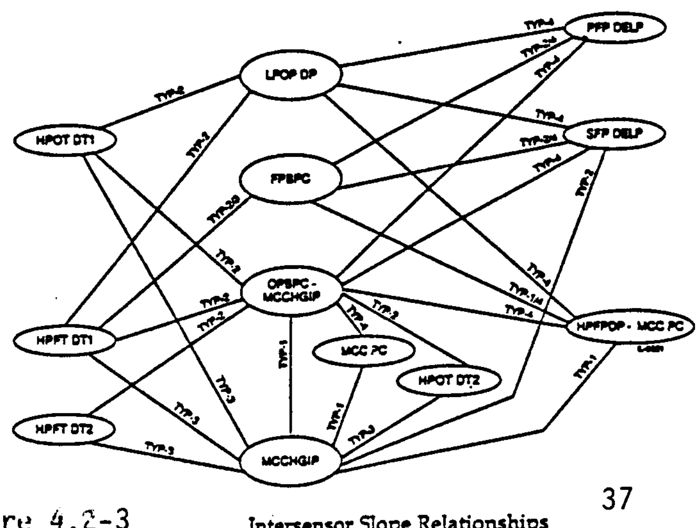


Figure 4.2-3 Intersensor Slope Relationships among Dominant Sensors

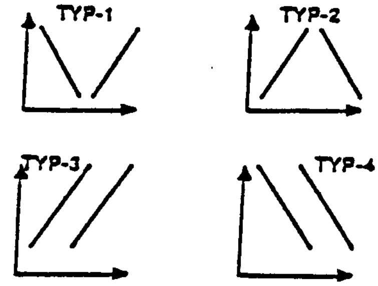


Figure 4.2-4 Slope Relationships

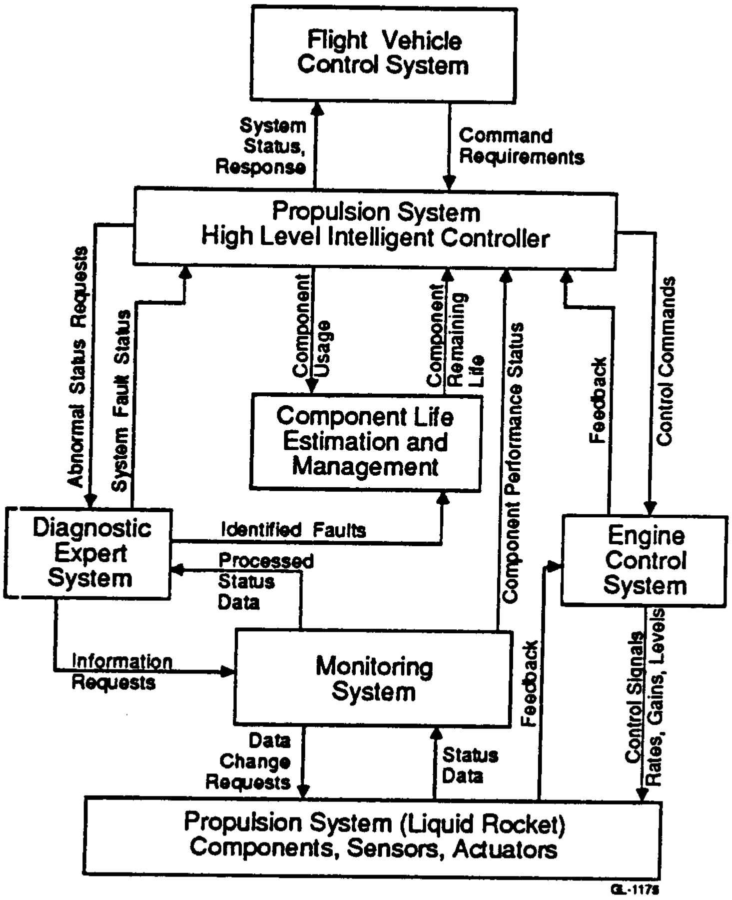


Figure 4.2-5 Propulsion System Intelligent Control and Monitoring

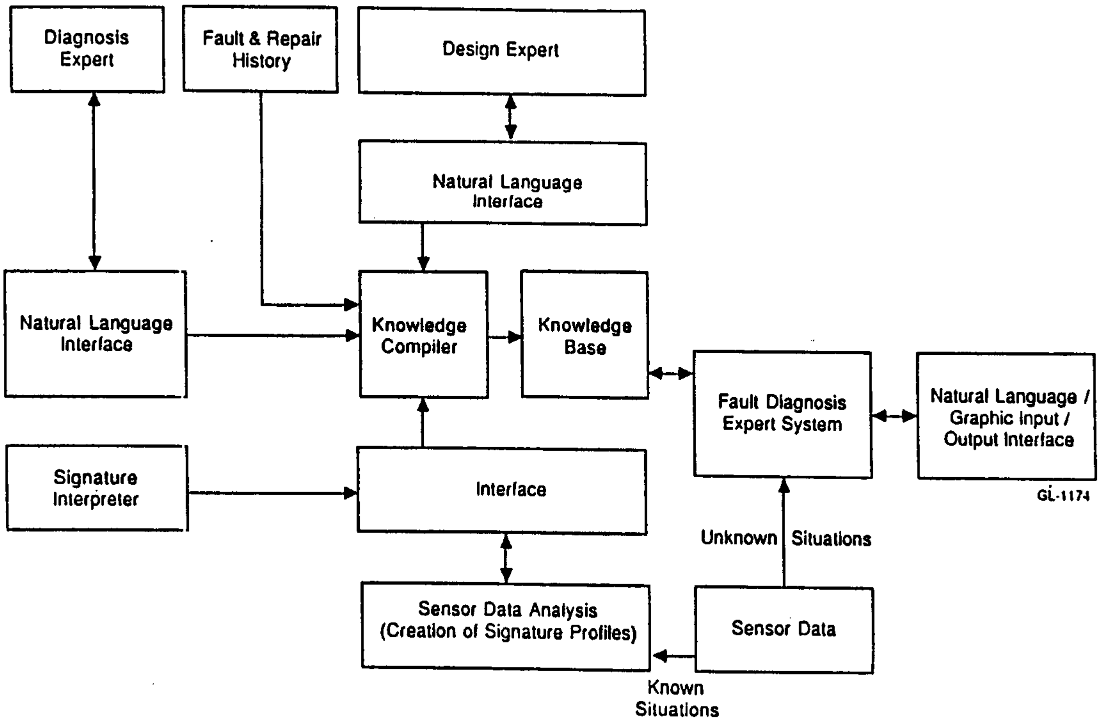
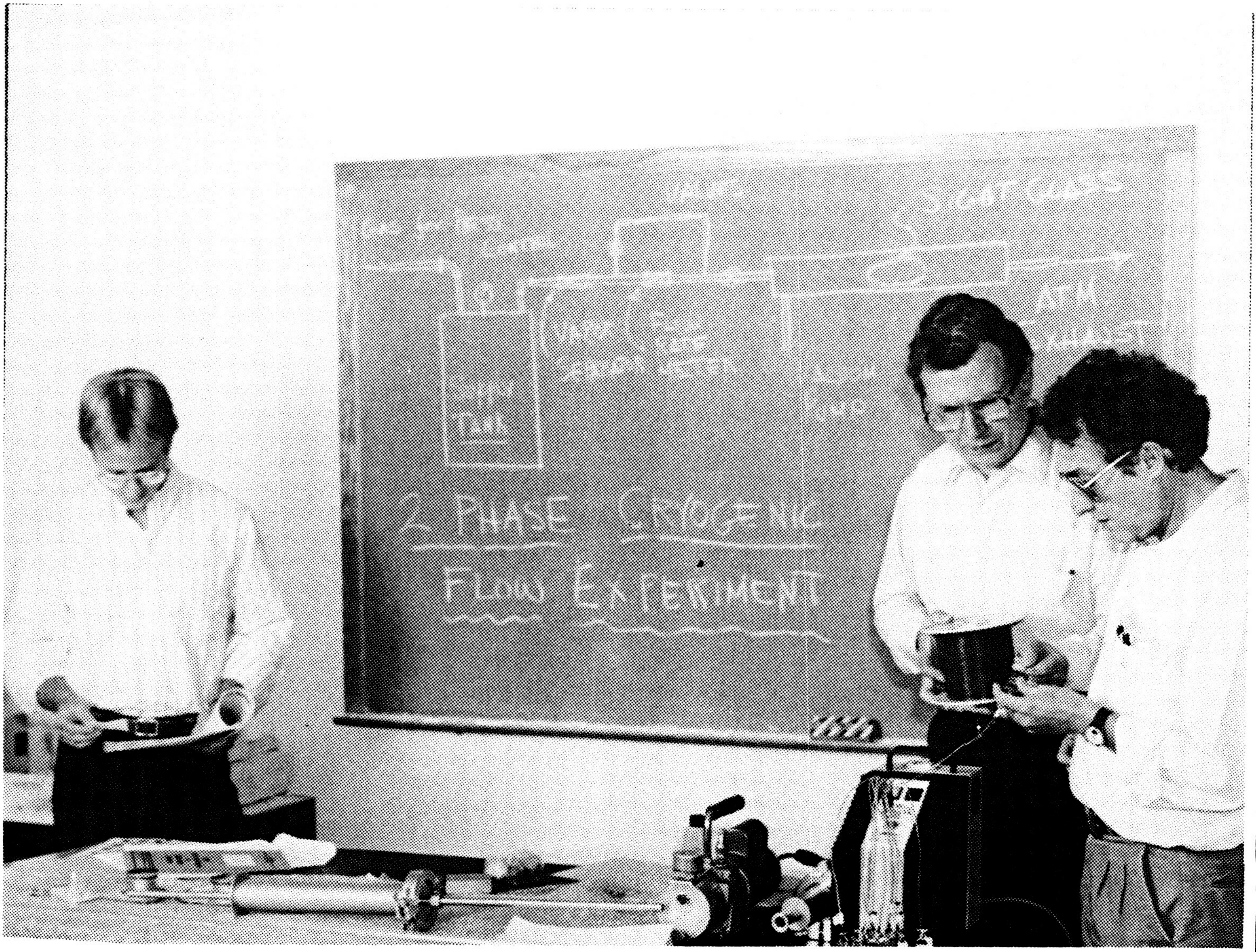


Figure 4.2-6 Architecture of the Integrated Expert System



LIQUID CRYOGEN TRANSFER AND STORAGE IN LOW GRAVITY

SECTION 4.3

4.3 LIQUID CRYOGEN TRANSFER AND STORAGE IN LOW GRAVITY

4.3.1 Principal Investigators:

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Other Investigators:

DR. FRANK COLLINS, CASP/UTSI
MR. ALI HEDAYATPOUR, CASP/UTSI GRA
MR. TERRY MCGEE, CASP/UTSI GRA

4.3.2 Objective:

The objective of this project is to perform the research and development that leads to on-orbit storage and refueling facilities for liquid propellants and cryogenics.

The ultimate commercial product will be an on orbit resupply station. Intermediate products are software and hardware that will naturally occur in the course of the development of the orbiting station.

Reusable propulsion stages and serviceable long-life satellites and space platforms will be key elements of the future U.S. space infrastructure. Refueling these spacecraft will require on-orbit facilities for storing and delivering liquid propellants. Our objective is to acquire experimental data and develop validated computer models applicable to future requirements for low-gravity fluid storage, acquisition, and transfer systems, with emphasis on technology for cryogenic systems.

4.3.3 Approach:

The project is being performed jointly by Boeing and CASP investigators. The CASP investigators will perform the following task:

A. Two Phase Fluid Physics

The objective for this project segment is to develop sufficient analytical and experimental expertise for understanding the role of two phase physics as it impacts the technology development for successfully achieving cryogen liquid transfer and storage in Earth's orbit. For this end the following two specific tasks were identified to be subjected to further study by CASP: (1) transfer line childown, and (2) receiving tank childown.

The work on both of these tasks should involve sufficient depth of analysis in order to provide realistic prediction capabilities on the performance of the transfer process regardless of the fluid used and the size of the process. The reliability of the analyses should be verified via both 1-g and low-g tests. Also, this task calls for the integration of the final software model of the process to allow for a feed back corrective mechanism between the line childown process and the receiving tank childown and fill.

The Boeing investigator, Dr. J. S. Meserole, will perform the second task identified as:

B. Liquid Acquisition

This particular task is aimed at developing the technology for liquid hydrogen acquisition in low gravity. Specifically, it involves the testing in liquid hydrogen of a screened-channel liquid acquisition device (LAD). This type of LAD incorporates channels with fine mesh screen for separating liquid from vapor and thereby enabling the withdrawal of vapor-free liquid in low gravity. The test objective is to determine how the type and temperature of the pressurant gas affect the pressure difference across the screen at which vapor begins to pass through into the channel.

A passive fully reusable surface tension liquid acquisition device (LAD) which incorporates channels with fine mesh screen for separating the liquid and vapor will be developed and tested. A demonstration flight experiment is planned for the Shuttle at a later date.

4.3.4 Accomplishments For FY 88

4.3.4.-1 Transfer Line Childown - Analysis

Refueling with liquid fuel in the low gravity environment of Earth's orbit involves several distinct procedures each of which must be accomplished successfully. The most critical of these procedures are:

a) docking of the vehicle to the fuel storage tank,
b) the childown of the fuel line connecting the storage tank to the vehicle, (the transfer line),

c) the chilldown of the vehicle fuel tank,

d) the expulsion of the liquid fuel from the storage tank, and

e) the filling of the storage tank with liquid fuel to the maximum capacity and without significant loss of fuel.

It is desired to accomplish these procedures with the fastest time possible and preferably without significant losses of fuel.

The transfer line needs to be chilled in order to allow only a single phase liquid to enter the vehicle fuel tank. However, there is also an added need to study the transfer line chilldown process due to the fact that large fluid pressure oscillations have been observed to occur in the initial phases of the process. It is conceivable that such oscillations might adversely effect the line couplings and thus impair the transfer process.

Technically the transfer line chilldown process involves establishing the variation of the temperature and fluid phase and velocity history in a cylindrical tube with a specified set of initial temperature and pressure conditions and for a given mass inflow of cold liquid. Such a problem has been studied extensively in the past in connection with nuclear reactor safety analyses. However, the difference between the present application and the previous studies is that the chilldown process is to be performed in low-gravity environment while the latter studies were for one-g applications.

After careful review of the existing literature on two-phase flows in pipes it was decided to solve the one dimensional model of the problem first. The mathematical model adopted is the one-dimensional form of the separated two-phase flow equations. This model is well suited for resolving both the initial pressure transients as well as the development of the long term steady flow. This model is described by six, volume-averaged conservation equations for the mass, energy, and momentum balance and for each phase (in this case liquid and vapor). The equations are the following:

Liquid continuity:

$$\frac{\partial}{\partial t}(\alpha_l \rho_l) + \frac{\partial}{\partial z}(\alpha_l \rho_l u_l) = -\dot{m}_l''' \tag{1}$$

Vapor continuity:

$$\frac{\partial}{\partial t}(\alpha_v \rho_v) + \frac{\partial}{\partial z}(\alpha_v \rho_v u_v) = \dot{m}_l''' \tag{2}$$

Liquid momentum:

$$\frac{\partial}{\partial t}(\rho_l \alpha_l u_l) + \frac{\partial}{\partial z}(\rho_l \alpha_l u_l^2) + \alpha_l \frac{\partial P_l}{\partial z} - \Delta P_{li} \frac{\partial \alpha_l}{\partial z}$$

$$= \tau_i''' - \dot{m}_l''' u_i + \tau_{wl}''' \tag{3}$$

Vapor momentum:

$$\frac{\partial}{\partial t}(\rho_v \alpha_v u_v) + \frac{\partial}{\partial z}(\partial_v \alpha_v u_v^2) + \alpha_v \frac{\partial P_v}{\partial z} - \Delta P_{vi} \frac{\partial \alpha_v}{\partial z}$$

$$= -\tau_i''' + \dot{m}_l''' u_i + \tau_{wv}''' \tag{4}$$

Liquid energy:

$$\frac{\partial}{\partial t}(\rho_l \alpha_l h_l) + \frac{\partial}{\partial z}(\rho_l \alpha_l u_l h_l) = -\dot{m}_l''' h_{l,sat} + q_{s,l}''' \tag{5}$$

Vapor energy:

$$\frac{\partial}{\partial t}(\rho_v \alpha_v h_v) + \frac{\partial}{\partial z}(\rho_v \alpha_v u_v h_v) = \dot{m}_l''' h_{v,sat} + q_{s,v}''' \tag{6}$$

In the above equations, ρ, u, P, h, and α are the density, the averaged axial velocity, the pressure, the enthalpy, and the void fraction respectively. The independent variables for this one-dimensional model are the time, t and the axial distance along the tube, z. The subscripts l and v denote the respective variables for the liquid and vapor phases. The term ΔP_{li} or ΔP_{vi} is the pressure difference between the liquid-vapor interface and the liquid phase or the vapor phase, respectively. The governing equations given above contain the following unknowns:

$$u_l,\ u_v,\ \alpha_l,\ \alpha_v, \rho_l,\ \rho_v,\ P_l,\ P_v.$$

Since these equations were derived using averaging procedure the dependent variables (the unknowns shown above) are in terms of quantities averaged over the cross section of the tube. Also, the averaging process gives rise to a number of source terms which need to be established before a solution can be obtained. These terms are the following:

$$\tau_{wl}''', \tau_{wv}''', \tau_i''', q_{s,l}''', q_{s,v}''', \dot{m}_l''',$$

which appear on the right hand sides of equations (1) - (6). These terms account for the radial fluxes of momentum and heat between the tube walls and the adjacent fluid and also at the liquid-vapor interfaces. These functions are normally determined empirically and primarily depend on the type of two-phase flow at that section. Since these functions also affect the solution to the averaged quantities it is clear then that they should be determined with a great deal of care. Normally, in one-g applications these functions are modeled from several statistically meaningful measurements of different two-phase flow regimes. Alternatively, good working models for these functions may be obtained from conservation principles for each specific flow regime. In micro-gravity environment, due to the lack of experimental facilities, only the latter method may be pursued. However, before these functions are modeled it is necessary to perform a minimum number of experiments on one-dimensional two-phase flow in micro-gravity in order to establish the most probable two-phase flow regimes for given operating conditions.

Once viable models of the source terms are established then it is possible to integrate the governing equations (1)-(6) in order to obtain the time histories of the various averaged variables. It is obvious that a numerical method is the only way to solve these equations. Depending on the equations themselves, and whether a steady or a transient solution is required, it is possible to use either an implicit or an explicit finite difference method. There are advantages as well as drawbacks to each method which is not possible to explore in this report. Since we are interested in both the initial pressure transients as well as the final steady solution, a semi-implicit finite difference technique will be used in the present case to solve equations (1)-(6). This technique is outlined below.

First the tube is divided into cells in the axial direction with nodal points at the boundary of each cell as shown in Figure 4.3-1. A subscript j for the variables refers to the axial node location and a superscript n to the iteration step of the current time step. For simplicity, values known from the previous time step are written without superscripts. All the calculations described below proceed from the entrance to the tube, from left to right in Figure 1 and thus variables values immediately to the left of the current node are assumed known.

First the liquid continuity equation, (1) is written in terms of finite differences as follows to obtain the liquid mass:

$$M_{lj}^{n+1} = M_{lj} + \frac{\Delta t}{\Delta z}(G_{lj-1}^{n} - G_{lj}^{n}) - \Delta t\, \dot{m}_{lj}^{'''n}$$

in the above M $=\alpha\rho$ and G $=\alpha\rho u$. From this solution the void fractions are determined at the node j. Next, the vapor continuity and energy equations are solved together to obtain the vapor temperature, density and flow rate. The vapor energy equation, (6), is implicitly finite differenced in the following way:

$$H_{vj}^{n+1} = H_{vj} + \frac{\Delta t}{\Delta z}[(Hu)_{vj-1}^{n+1} - (Hu)_{vj}^{n+1}] + \Delta t(q_{vj}^{'''n+1} + \dot{m}_{lj}^{'''n+1}\, h_{v,sat})$$

Where $H = \rho\alpha h$. Rearranging the above equation it is possible to solve for h_{vj}^{n+1}, where h_v is given by:

$$h_v = C_{p_v}(T_v - T_sat) + h_{v,sat}$$

Next the vapor continuity equation is also implicitly finite differenced as follows:

$$M_{vj}^{n+1} = M_{vj} + \frac{\Delta t}{\Delta z}(G_{vj-1}^{n+1} - G_{vj}^{n+1}) - \Delta t\, \dot{m}_{lj}^{'''n+1}$$

After several algebraic manipulations and rearrangements of terms a quadratic equation in the vapor temperature T_{vj}^{n+1} is obtained which is solved for the vapor temperature at that node.

With the vapor temperature determined, various heat transfer rates can be calculated for the updated source terms. Also, various vapor properties can be calculated with the new temperature and especially the vapor density. The vapor continuity equation is finite differenced as follows to yield the vapor mass flux and velocity:

$$G_{vj}^{n+1} = G_{vj-1}^{n+1} - \frac{\Delta z}{\Delta t}(M_{vj}^{n+1} - M_{vj}^{n}) - \Delta z \; m_{lj}^{'''n+1}$$

$$u_{vj}^{n+1} = G_{vj}^{n+1} / \; M_{vj}^{n+1}$$

At this point the values of the dependent variables, H_v, G_v, M_v, and u_v at the (j-1)th node are all known in order to calculate their values at the jth node.

Next, the shear stress terms [the forcing functions in equations (3) and (4)] are evaluated from the known values of the void fractions, velocity and density of both the liquid and vapor phases. The vapor momentum equation is then finite differenced to yield the vapor pressure. The calculation for the pressure is started from the right side of the tube since the exit pressure is assumed to be known. The remaining equation is the liquid momentum equation, (3), which is finite differenced to yield an expression for G_{lj}^{n+1} . All of the equations except the liquid energy equations are solved iteratively at each time step starting with n = 0 until convergence on all variables is obtained. Once the solution has converged then the liquid energy equation is solved for both H_l and the liquid temperature T_l at that time step. The time is then stepped a single step and the solution scheme is repeated again. The overall solution scheme described above is shown in the flow chart of Figure 4.3-2.

A computer program to solve the problem according to the scheme described above has been written. The program is being checked with a sample problem in which the working fluid is water.

4.3.4.-2 Transfer Line Childown - Experiments

It was decided to perform several 1-g experiments on the one dimensional two-phase flow problem in which the working fluid is a cryogen. These experiments will serve the dual purpose of validating the numerical model described in task A above as well as to increase our understanding of the various two-phase flow regimes in the μ-g transfer line childown problem.

Equipment has been purchased to make general measurements of the properties of cryogenic fluid as it proceeds through a tube that is enclosed in a vacuum, as shown in Figure 3. The vacuum is used to simulate the conditions surrounding the transfer line in space. The portion of the transfer line inside the vacuum enclosure will be made from stainless steel. A fused quartz section will be placed near the middle of the stainless steel tube and positioned in a viewing window on the vacuum wall. This transparent section will allow for visual determination of the state of the two-phase flow in the tube. The vacuum-jacketed section will be instrumented to measure flow rate, wall temperature, pressure, flow quality (void fraction), wall skin friction and wall heat flux. A high speed data acquisition system has been purchased plus temperature, pressure, and wall thin film heat transfer gauges. A meter to measure the fluid void fraction (quality) is being designed.

4.3.4.-3. Receiving Tank Childown

Tank childown and fill constitutes a crucial step in any refueling process since this process will be repeated every time a refill of the Space Transfer Vehicle is performed. This process will involve initially lowering the wall temperature of the empty receiving tank from ambient to a temperature close to the liquid temperature. This is basically accomplished through the introduction of a small charge of liquid into the tank either through a spray or a jet which should contact the tank wall. In this instance heat is rejected from the wall through conduction and is absorbed by the liquid in the form of latent heat of vaporization. This process is repeated until the tank wall reaches the desired temperature. However, due to the liquid evaporation mechanism the tank pressure will rise.

The amount of coolant needed to lower the tank temperature from its ambient value to a final value can be easily calculated through a thermal balance analysis if the thermodynamic properties of both the coolant and the tank material are known and ideal conditions are assumed. However, the time needed to accomplish this task is not as easily calculable. The cooling rate is a strong function of the cooling technique employed. The method for calculating this rate varies according to whether a jet is used or a spray. In both cases, however, the cooling rate is predicted by analyzing the hydrodynamic behavior of the cold liquid upon impingement on a hot surface. As an example, the cooling rate will be different for a cold drop impacting a hot surface and for a liquid film moving on a surface. For both cases realistic hydrodynamic-thermal models can be constructed to predict cooling rates once the fluid behavior at and during impact is known. Fluid behavior upon impact can be classified through experimental means. For a drop, it is well known that its shape evolution, and hence the heat transfer rate, when it impacts a hot plate is a function of the Weber number. The Weber number is the ratio of the drop's kinetic energy to its surface energy due to surface tension. In order to determine the cooling rate it is possible to use the extensive amount of research that already exists for both spray cooling and liquid jet cooling.

Of course all of the work performed to date on spray and jet cooling has been for terrestrial conditions. It is hard to believe that the hydrodynamics and thermodynamics of this problem are substantially affected by gravity. However, one area where gravity influence may be felt is in the maximum drop size that can be obtained under low-gravity conditions. It is possible to imagine that drop morphology upon impact will be different for larger drops. However, this problem can be suppressed by imposing a maximum allowable drop size.

There are two areas of deficiency in our knowledge that can be immediately identified. One is whether liquid drop disintegration upon impingement on a wall at cryogenic temperatures obeys the established Weber number classification for water. The second is whether this classification is also valid for low-gravity impact environment. Both of these questions can be easily answered with a few simple experiments using either drop towers or parabolic trajectory airplane flights. A research program has been initiated to address these two specific questions. A thorough literature survey has been completed regarding the drop impact problem and an experiment is being designed to assess the applicability of the Weber number dependence of drop heat transfer for liquid nitrogen.

4.3.4.-4. Liquid Acquisition Experiment

Building on prior research and design work at Boeing, we acquired a new LAD test article built to our design for tests with liquid hydrogen. The LAD utilizes a 325x2300 double dutch twill weave screen which is bonded to a perforated plate that provides rigidity.

The experiment apparatus was assembled at the company's hazardous test facility in Tulalip, Washington. The LAD channel was suspended inside a cylindrical container which itself was immersed in a liquid hydrogen dewar. The tests involved the emptying of a container of liquid hydrogen by expelling liquid out the top of the LAD channel against a 1-g gravity force. This is actually a more stringent test of the ability of the screen to prevent vapor ingestion than an LAD would encounter in log-g operation. To determine how the type and temperature of the pressurant gas affects LAD performance the liquid hydrogen container was pressurized in separate tests by warm and cold helium, warm and cold normal hydrogen, and cold para-hydrogen.

The experiment was conducted in September, 1988. We have completed a preliminary assessment of the data and are confident that the experiment objective has been mostly achieved. Detailed analysis of the data will commence in October.

4.3.5 Future Plans:

Transfer Line Chilldown - Analysis

The one-dimensional two-phase flow code will be completed and verified by duplicating documented cases. Subsequently the code will be run with liquid nitrogen as the working fluid under a matrix of conditions simulating both low-g and μ-g conditions.

Transfer Line Chilldown - Experiments

The design and construction of the quality meter will be completed. Wall heat transfer gauges will be designed and manufactured. The experiment will be assembled and performed using liquid nitrogen as the working fluid. This experiment will be designed to be autonomous and compact in order to allow it to be performed on board a KC-135 airplane. We are planning to perform such low-gravity experiments.

Receiving Tank Chilldown

The design and construction of cryogen drop impact experiments will be completed. Initial formulation of the theory on the heat transfer from configuration drops will also be completed.

Liquid Acquisition Experiment

Our plan for the upcoming fiscal year is to complete the data reduction and to document the test results. A complete report will appear in an upcoming CASP quarterly report.

Currently planned for the continuation of Boeing research in kind under this task in 1989 is an experiment to demonstrate unvented filling of a liquid hydrogen tank. Unvented filling of an initially evacuated tank is the primary method under consideration for transferring cryogens in space. The objective of the experiment will be to measure the rate of condensation of the hydrogen vapor as a function of the fill pressure and the amount of mixing induced by the liquid inflow. The vapor is present from flash boiling that occurs at the beginning of the fill. Much of the apparatus assembled for the liquid acquisition device testing this year can be readily adapted for this new experiment.

4.3.6 Publications

1. B. N. Antar, 1988 Cryogenic Fluid Management in Space. NASA/ASEE Summer Faculty Fellowship Program Report.

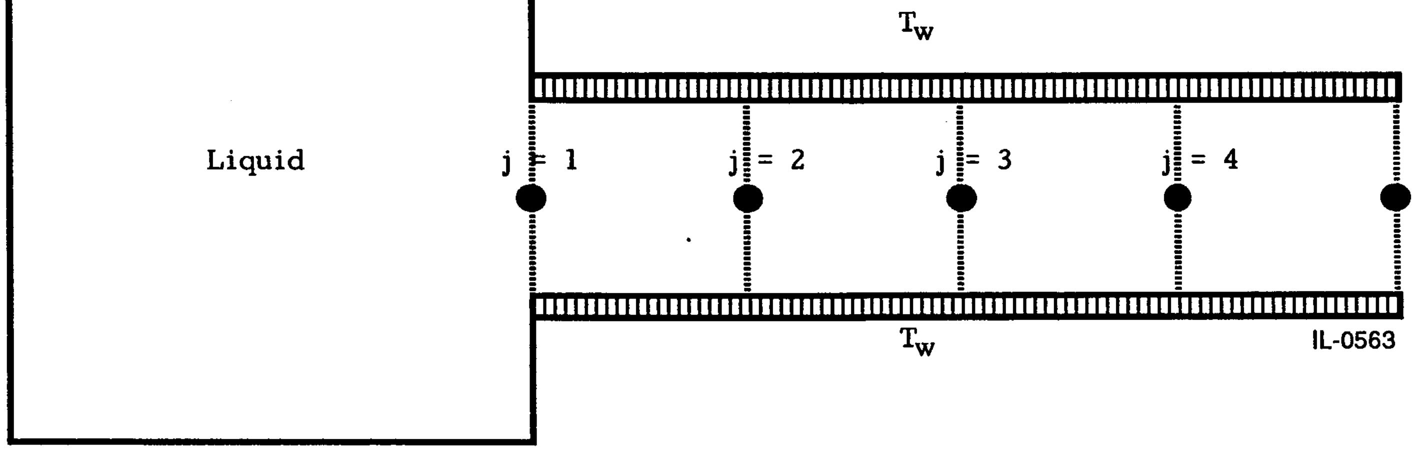


Figure 4.3-1 Schematic of the discretization method for the line childown problem

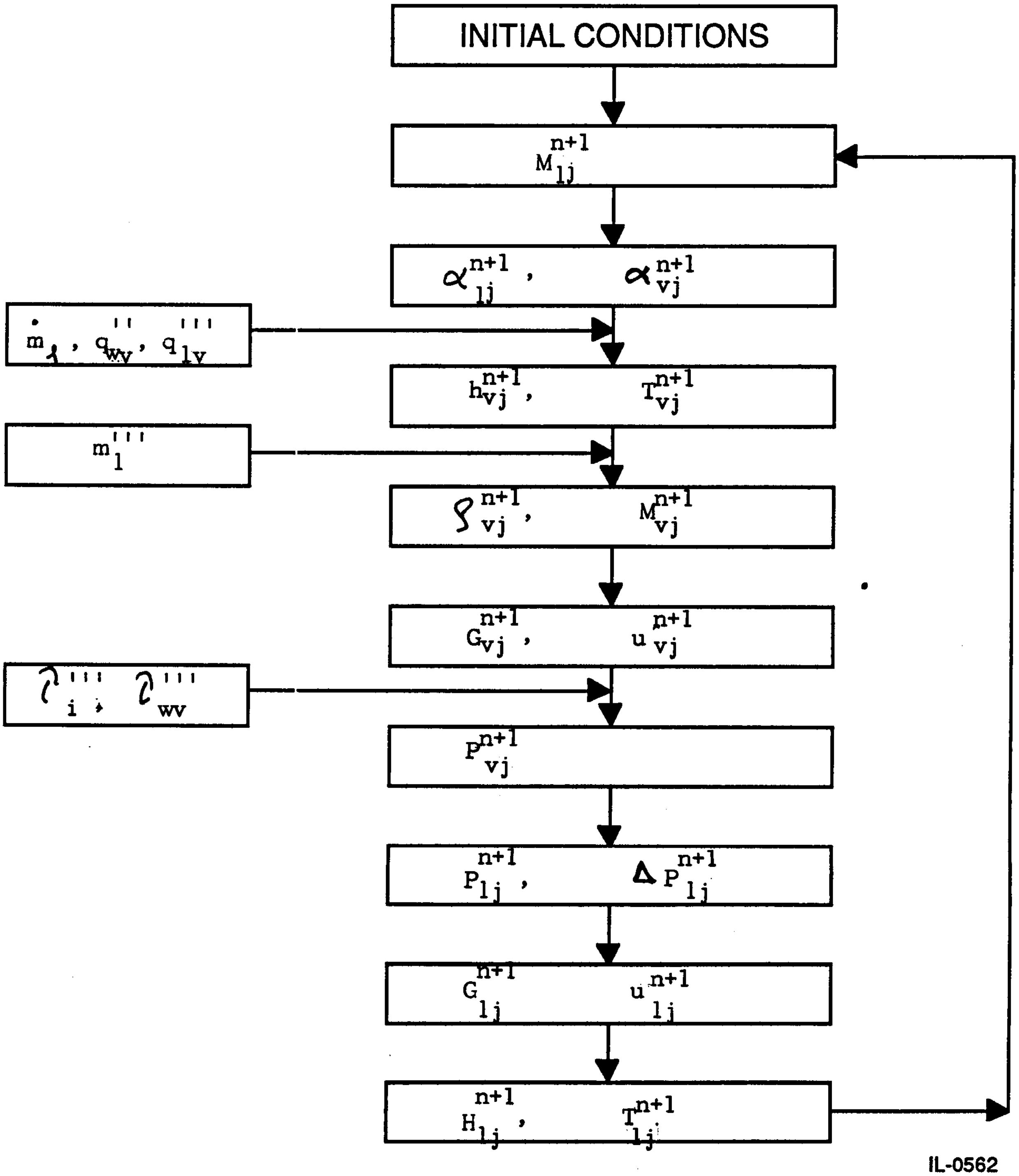


Figure 4.3-2 Flow Chart for the Numerical Solution of the Transfer Line Chilldown Problem

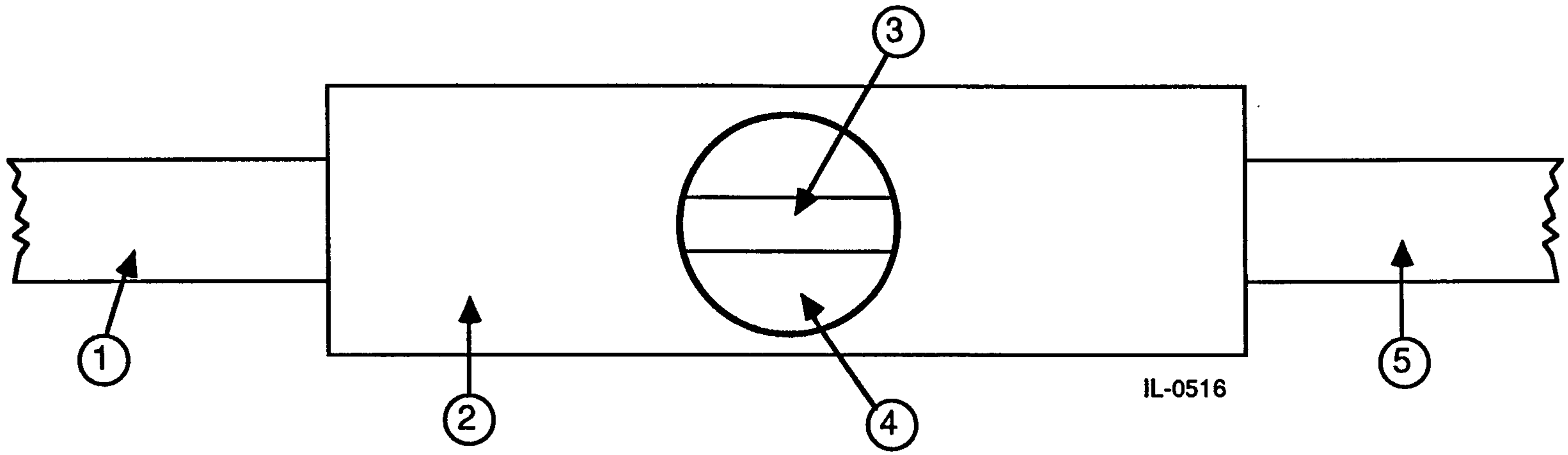


Figure 4.3-3 Cryogenic Transfer Line Experiment
1) Insulated inlet line;
2) Vacuum-jacket section;
3) Fused quartz section of cryogenic line;
4) Viewing window on vacuum-jacket section;
5) Insulated outlet line

4.4 SPRAY COMBUSTION STABILITY

4.4.1 Principal Investigators:

DR. ROBERT JENSEN, ROCKETDYNE DIV., ROCKWELL INTERNATIONAL CORPORATION
DR. ROY SCHULZ, CASP/UTSI

4.4.2 Objective:

The objective of the project is to assist in the commercial development of liquid-fueled rocket motors by assisting in the effort to improve existing capability to design, develop and enhance the performance of Liquid Propellant Engines. The effort of this program is focused on conducting research on spray combustion physics. The research has two parts: one part is the development, evaluation and verification of spray combustion math models and sub-models; the second part is to perform critical experiments with both combusting and cold sprays using advanced optical diagnostic technology. The experimental objectives are the definition of spray dynamics and combustion characteristics resulting from the spray dynamics, including possible combustion instability modes.

The commercial product will be computer codes that provide information to design efficient and stable operating liquid fueled rocket engines.

4.4.3 Approach:

The Principal Investigator will conduct both theoretical and experimental tasks under two phases of this investigation. Phase 1 is a baseline numerical spray model evaluation utilizing the ARICC Code obtained from Rocketdyne. All sub-models and modeling assumptions that address droplet or droplet group heat and mass transfer will be tested and evaluated.

Phase 2 is a study to investigate acoustic absorption/emission/transmission characteristics of two-phase flow regimes in sprays. The study begins with a survey and analysis of the literature and a review of relevant experimental data. Those results of the study that warrant inclusion or testing within the framework of ARICC will be identified and tested parametrically.

The purpose of this project is to assist in the development of new computational tools that can be used to predict the behavior of liquid rocket motor combustion systems. The combustion systems are typically based on the injection of liquid fuels and oxidizers into combustion chambers through holes or tubes called the injector elements. The injector elements pass through the dome or top of the combustion chamber which is typically a plate called the injector plate. The number of such injector elements range from a single element to hundreds of elements arranged and distributed in patterns over the injector plate. The fuels and oxidizers are generally injected as liquid jets that interact, atomize, mix, evaporate, and burn. The injected jets might be designed to impinge directly on one another, in groups of two, four, or six jets; or the fuels and oxidizer jets may be co-annular, that is, co-axial and annular. The fuels and oxidizers that have been used for rocket propulsion include hypergolic (auto igniting upon contact with one another) and non--hypergolic propellants. Therefore, some rocket motors require a system for igniting the propellants and often a means of sustaining the flame zones in the combustion chamber. Often, pressure fluctuations in the combustion chamber occur which are of sufficient magnitude to destroy or seriously damage the engine through mechanical or thermal stresses initiated by the fluctuations. These pressure fluctuations, whether of an acoustical (sound pressure) nature or of lower frequency, higher amplitudes, interact with the injection, atomization, mixing, evaporation and burning processes of the fuel and oxidizer jets. Then, the spray combustion processes couple to the fluctuating pressure environment, and spray combustion instability occurs.

One of the first steps to the development of a computational and methodological approach to analyzing spray combustion stability or instability is to formulate a steady spray combustion computer code that can treat a burning spray from a single injector element which includes both the fuel jet and the oxidizer jet.

The Rocketdyne Company has developed an injector spray combustion model called the Advanced Rocket Injector Combustion code (ARICC). This code supersedes previous Rocketdyne spray combustion codes, such as the Coaxial Injection Combustion Model (CICM). The power of the ARICC code is that it provides the capability of computing the strongly coupled spray-dynamics and gas-phase flow fields. This capability provides not just the global gas phase flow, but also the details of the flow about the spray particles or droplets, or groups of droplets. This "local" flow is necessary in order to analytically define the spray particle (or particle group) heat and mass transfer rates. In addition, the ARICC code provides the capability to compute the atomization process of a liquid column (LOX jet) surrounded by an annular stream (highly compressed, dense H_2 or H_2/H_2O gases).

An important feature of any rocket motor liquid fuel injection and combustion code is that it contains models of droplet evaporation that incorporate high pressure effects on the particle or droplet heat and mass transfer, and possibly, aerodynamic drag processes. These include non-ideal gas equations of state, mass transfer laws that have the correct form of the so-called driving force for mass transfer, gas-phase solubility in the droplets, and so on. Also, the presence of a turbulent gas phase surrounding the droplets must be taken into account if the turbulence augments the heat or mass transfer processes, or particle drag forces. Conversely, the presence of dense clouds of particles, fragmenting liquid sheets, and other dense phase structures affects the production and dissipation of the gas phase turbulence. ARICC contains many of these effects, or physical phenomena, which must be evaluated and further developed in order to anchor the code as a general tool for predicting spray combustion phenomena.

Further, a methodology for using ARICC to identify potential combustion instability modes must be developed for spray combustion systems. These instabilities might be stimulated or driven by pressure field characteristics such as longitudinal and transverse acoustic pressure fields, or may incorporate shock/detonation/deflagration-type pressure fluctuations which are of greater magnitudes but may not be periodic.

This introductory discussion is far from being inclusive in terms of a description of the complex phenomena that arise in rocket motor spray combustion processes. However, it does indicate that the Rocketdyne Company has been working for several decades to prepare increasingly more physically realistic mathematical models of spray combustion for use in the evaluation and development of rocket motor injector technology.

4.4.4 Accomplishments in FY88

A literature search and review was done to obtain data on:

a) Background and formulation of the ARICC code, including the Conchas - Spray and KIVA codes which have related numerical solution algorithms.

b) Liquid jet break-up, atomization, and spray formation.

c) Data and models for convective heat and mass transfer processes for particles and droplets.

d) Droplet break-up and shattering by shock and strong compression waves.

e) Combustion instability in rocket motors.

f) Thermodynamics of phase interfaces, including treatment of surface tension and transport across a phase-change boundary.

g) Turbulence modeling in gas-particle flows.

4.4.4.-1 Implementation of the Rocketdyne ARICC Code

A review and presentation was provided to Rocketdyne of the CASP Spray Combustion Stability Program. Dr. R. Jensen and Dr. Pak Liang defined the investigation of the evaporation submodel of ARICC as being the first step for CASP personnel to pursue in the evaluation of ARICC. Dr. Liang identified the version of ARICC that Rocketdyne would supply to CASP as the archival, benchmark copy from which to begin the evaluation.

In June, Dr. Pak Liang sent to Dr. Schulz a version of the ARICC code to begin the investigation of the evaporation sub-models. This code was installed on the VAX computer system of The University of Tennessee Space Institute. In order to run the code to obtain complete solutions, a main frame computer such as Cray or Cyber machine is required (or, a dedicated super mini computer). Thus, arrangements were made to obtain a telephone access port to the NASA Marshall Cray Computer.

Work was done to become familiar with the Engineering Analysis and Data System (EADS) that controls the processing of communication and other information on the Marshall Computer System. The ARICC code was successfully installed on the account/directory during the month of October.

4.4.4.-2 Research Facility Design

A design concept for a variable-pressure spray/atomization chamber was prepared. The design concept included the basic design for operation, the size scales and so forth. Then, the UTSI site was investigated to locate a place to install the spray research facility.

Cost estimates were prepared for the detailed engineering design, fabrication and installation of the spray chamber. In addition, costs were estimated for preparing the UTSI test site where the spray chamber (Figure 4.4-1) would be installed. This included the costs of providing compressed gases, water, electrical power, and cryogenic fluids such as LN_2 and LOX.

4.4.4.-4 Diagnostics

Determination of experimental methods for investigating the fluid mechanics of sprays is in progress to identify the optically-based methods, including hardware, data acquisition, data reduction and data display, for obtaining measurements of spray/atomization processes associated with single and multiple injector elements. These methods include doppler/particle sizing interferometry (LDV-PSI), shadow spectrometry, laser induced fluorescence, and similar methods that have been reported and evaluated in the literature.

UTSI has an active program of research in these fields and both experimental and theoretical programs have been conducted at UTSI. This expertise is being utilized to formulate the CASP experimental program.

4.4.5 Future Plans

4.4.5.-1 Theoretical Model Development

The literature will continue to be studied and analyzed in the areas of atomization, sprays, heat and mass transfer processes, two-phase flow, turbulence, inter-phase interface transport phenomena, and acoustic/pressure wave effects on droplet breakup.

The ARICC code will be analyzed in depth to establish the meanings of the rather large number of parameters used to control the numerical behavior of the various code submodels, (e.g., numerical stability, heat and mass transfer, combustion kinetics, atomization, drop transport, turbulence and/or viscosity, injector cup effects, etc.) Particular emphasis will be put on the control and the physical/phenomenological meaning of those submodels that control the droplet evaporation processes including the heat and mass transfer to the drops or drop groups. Parametric studies will be performed that are designed to test the sensitivity of the numerical processes to the controlling parameters, including Reynolds numbers, "film" properties, driving forces for the heat and mass transfer, etc. These studies will be performed under the guidance and with the recommendations of the Rocketdyne Principal Investigator.

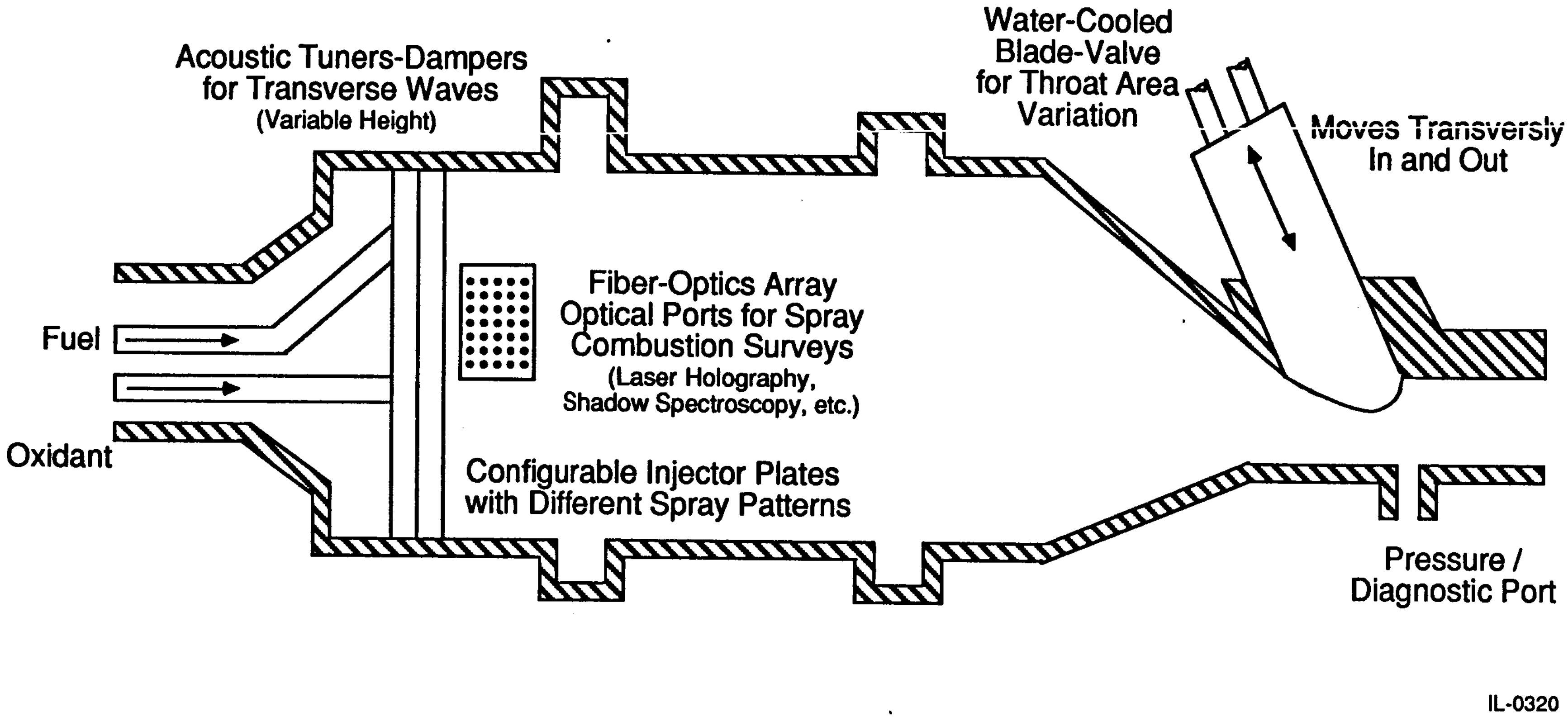
In rocket motors, the behavior of the combustion process is the result of a complex interaction between the combustor geometry and the sprays of a (typically) large numbers of injector elements. The injection, atomization, evaporation and burning of a spray from a single injector element may be only partially relevant to the actual rocket motor combustion process, where large numbers of elements (spray flames) are interacting. Inside a duct or combustor, multiple jets are known to mix and interact, creating flow patterns different from the pattern of flow created by a single jet in the combustor. Hence, a successful technology for application to the design of new rocket motors must incorporate multiple jet/spray mixing and burning phenomena. Therefore, during the next fiscal year, research will be done to define and perhaps evaluate numerical methods for predicting spray flows with and without combustion. These models may contain greatly simplified models of the spray in order to allow practical computations to be made of fully elliptic, reacting flows developed by multiple jets.

4.4.5.-2 Experimental Facility

The preliminary concepts for the variable-pressure spray facility chamber will be evaluated and an optimum configuration selected. The engineered design will take into account both the high pressures and high temperatures that could be associated with rocket fuel/oxidizer injection technology. The technology required for the application of optical (and other) spray diagnostics equipment will be integrated into the design of the spray chamber. All of the required interfaces, such as fluids, power, sensors, etc., for instrumentation of the facility, will be defined and incorporated into the design.

The site selected for the variable-pressure spray chamber will be cleaned up and prepared. All interfaces for fluids, power and control systems will be hooked up. The spray chamber will be installed after it is manufactured. Instrumentation and supporting systems will be installed at the site.

The variable-pressure spray chamber will be manufactured at UTSI. UTSI is one of the few ASME certified sites for high pressure coded vessel manufacturing. The spray chamber will be constructed together with the ducting necessary to exhaust the spray chamber.



Variable Chamber Pressure Spray Combustion Research Combustor

Figure 4.4-1

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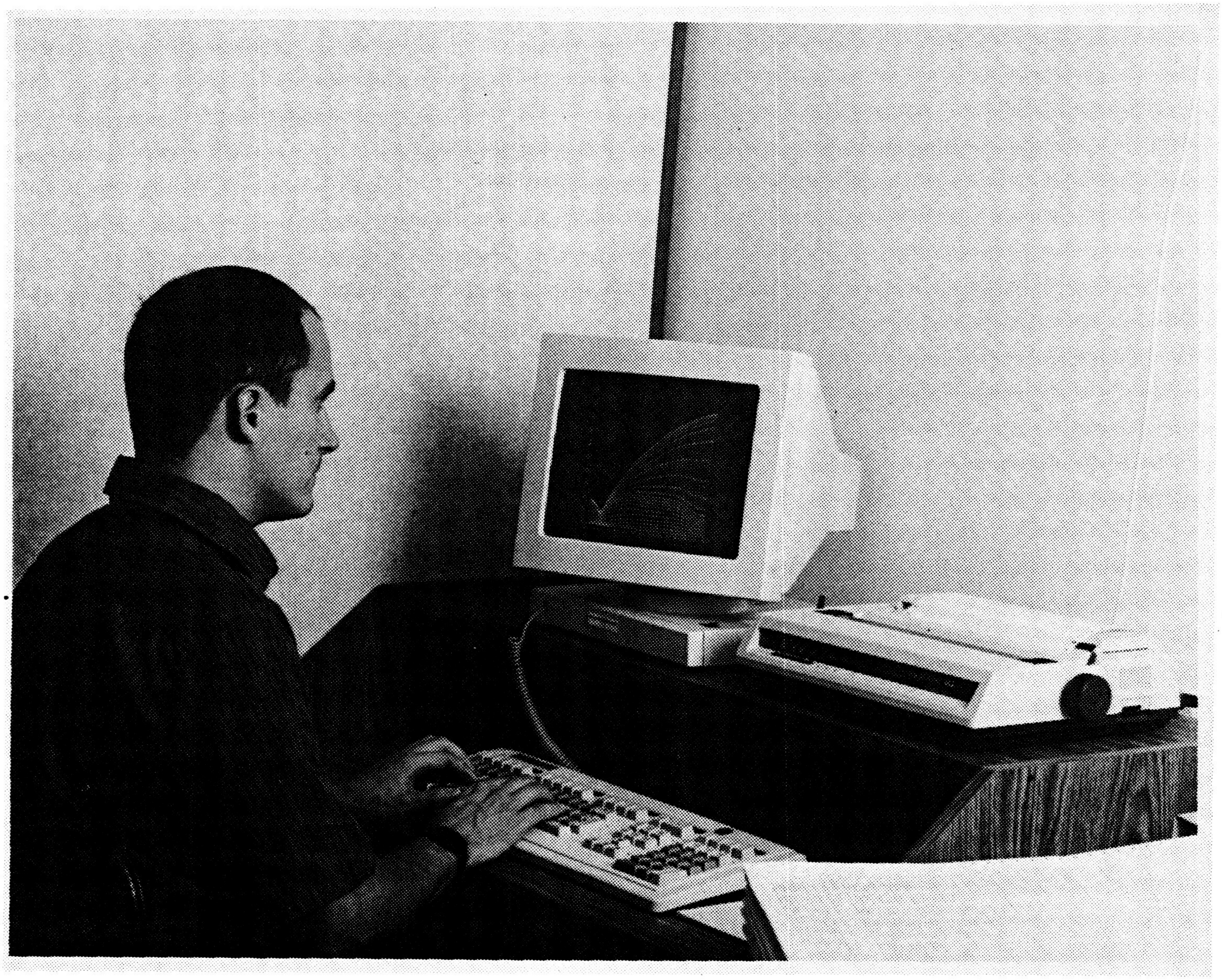


ADVANCED HIGH AREA RATIO NOZZLE

SECTION 4.5

4.5 ADVANCED HIGH AREA RATIO NOZZLE

4.5.1 Principal Investigators:

MR. ROBERT O'LEARY, ROCKETDYNE DIVISION, ROCKWELL INTERNATIONAL CORPORATION
DR. FRANK COLLINS, CASP/UTSI

Other Investigators:

MR. JOSEPH L. ORR, JR., CASP/UTSI GRA

4.5.2 Objective:

To develop computational techniques for the design of high-area-ratio nozzles, including both conventional and innovative, and to validate these models through testing.

The commercial product will be computer codes that can be used to design high-area-ratio nozzles for space propulsion systems.

4.5.3 Approach:

The initial phase of this project will apply the PARC2D fully-viscous Navier Stokes program to compute the flow field for several nozzles and critically compare the computation results with those of the Rockwell Science Center USA Navier Stokes Code and with the latest JANNAF methodology. Enhancements to the PARC2D code are planned to provide for equilibrium and non-equilibrium flow, for improved turbulence modeling and for exit rarefaction.

The first task will be to apply the PARC2D code to the SSME nozzle for inviscid, constant gamma conditions and to compare the computed flow field with the Rocketdyne predictions. The second task will be to use the same code to compute the flow field of the Rocketdyne Advanced Space Engine (ASE) nozzle assuming a constant gamma, both with and without viscosity, and to compare the predictions with those of the latest JANNAF methodology. The addition of equilibrium chemistry to the PARC2D code for real gas calculations will follow the tasks above.

4.5.4 Accomplishments In FY88:

4.5.4.-1 SSME Nozzle Flow Field Calculations:

Three converged solutions to the flow field in the SSME nozzle were obtained using the PARC2D Navier Stokes computer code. All used the geometry provided by Rocketdyne but the first solution assumed a value of gamma equal to 1.25. The remaining solutions used the following parameters supplied by Rocketdyne: gamma = 1.20, stagnation pressure = 3000 psia, stagnation temperature = 6600° R.

A grid was generated for the SSME nozzle with 200 axial points, going from the injector face to the nozzle exit, and 100 radial points from the axis to the wall. Three additional grid planes were added downstream of the exit plane for the third solution. The grids were spaced uniformly in the radial direction and were clustered axially in the throat region. No grid modification was made to cluster in the vicinity of the embedded shock wave.

The computed Mach number profiles for gamma = 1.20 are shown in Figures 4.5-1a through 4.5-1d. The shock wave that results from the discontinuity in wall curvature downstream of the throat is clearly evident. Notice that the numerical values on the PLOT3D contours are incorrect because the PLOT3D program assumes that gamma = 1.4. In Figures 4.5-2a and 4.5-2b the first convergence attempt used gamma = 1.25 while gamma was 1.20 for the latter two. The difference in the two distributions gives an indication of the strong dependence of the solution upon the assumed average value of gamma and probably also indicates that no constant gamma, perfect gas, solution can match actual conditions in the engine. The negligible effect of the nozzle extension upon the Mach number distribution in the nozzle can be observed by examining Figures 4.5-2a and 4.5-2b. The second solution did not include the nozzle extension while the third one did and the effect upon Mach number was observed to be negligible.

Comparison of the present Mach number distributions with those computed by the Rockwell Science Center using the USA code (Figure 4.5-3) clearly demonstrates the similarity of the two results. Near the exit plane the Rockwell and CASP computations deviated by less than 0.4%. This comparison is even more significant since the USA and PARC2D codes use considerably different algorithms to solve the Euler equations. It must therefore be concluded that they yield the same flow field predictions for high-area-ratio nozzles and can be used for systematic comparison as greater complexity is added to the problem to be solved, such as turbulence and equilibrium chemistry.

4.5.4.-2 Inviscid ASE Nozzle Flow Field Calculations:

Two converged solutions to the flow field in the ASE nozzle were obtained, using the geometry supplied by Rocketdyne plus the following parameters: gamma = 1.20, stagnation pressure = 2000 psia, stagnation temperature = 6450° R.

Two grids were generated for the ASE nozzle. Both had 200 axial points and 100 radial. The axial grid started at the injector plate and proceeded beyond the nozzle exit plane. Both grids contained axial clustering in the region of the throat but the first grid had uniform radial spacing while the second had clustering near the axis to improve the stagnation pressure calculation. The second grid also clustered more axial grids in the combustion chamber. Neither grid was modified to provide clustering in the region of the embedded shock wave system.

The computed Mach number profiles are shown in Figures 4.5-4a through 4.5-4c. A shock wave formed at the discontinuity in wall curvature downstream of the throat, as in the SSME nozzle. In the ASE nozzle, however, the shock waves intersect and reflect within the nozzle.

The centerline and wall Mach number distributions are shown in Figure 4.5-5. While the flow continues to expand along the wall, along the centerline the flow expands until it reaches the shock wave intersection. Reexpansion begins again downstream of the intersection. The exit-plane Mach number profile shows the same flow features (Figure 4.5-6).

4.5.5 Current Status:

The work statement for this fiscal year called for the inviscid computation of the SSME flow field, along with a critical comparison with the computations performed by Rocketdyne, using their USA code. That task was accomplished, with virtually exact agreement obtained from the two computations.

The second task was to perform the inviscid and viscous flow field computations for the ASE nozzle and compare with Rocketdyne computations. The inviscid computation was completed but comparison could not be made with Rocketdyne USA code computations because they were not available. The viscous computations were not performed for several reasons, the most important being that a number of limitations of the viscous capabilities of the PARC code had been uncovered and their correction was not expected by Sverdrup Technology, Inc., AEDC Group until after October 1, 1988. The other reason was the renewed interest in the SSME nozzle flow field, especially with the new contour presently being tested at NASA Marshall Space Flight Center. Thus, the decision was made to initiate viscous computations first with the SSME nozzle, and then proceed to the ASE nozzle. It is probable that the large area ratio of the ASE nozzle will require use of the new blocked version of PARC, that will also be available after October 1, 1988.

A follow-on task was the reformulation of the PARC code to include equilibrium chemistry. This modification has been completed and is in the final stages of debugging. It is anticipated that this code will first be applied to the SSME nozzle, which can be accurately described by equilibrium flow.

The high-area-ratio nozzle computational results and the modifications to PARC2D to compute combusting equilibrium flows were presented at the PARC Code User Workshop, held August 22-23, 1988 at Arnold Engineering Development Center. Of the thirteen papers presented, 2 were contributed by CASP investigators.[1] The workshop indicated that PARC is gaining wide acceptance around the country for a wide range of applications. In addition, many organizations are successfully modifying the code for new applications, many of which will be of interest to CASP and their industrial partners. The workshop was attended by representatives from 12 aerospace companies, 5 government laboratories and 4 universities.

<u>4.5.6</u> Publications:

1. F. Collins, J. Orr, T. Saladino, "PARC Code Development at CASP/UTSI", PARC Code Users Workshop, held at Arnold Engineering Development Center, August 23, 1988.

<u>4.5.7</u> <u>Future Plans:</u>

There are a number of potential options that can be taken during the next year. The one chosen will be coordinated with the industrial partners early next year.

The first option would be to continue with the application of the PARC code to existing or designed nozzles, utilizing the October 1988 update of the code. Viscous, perfect gas solutions could be obtained for the SSME nozzle, modified SSME nozzle, ASE nozzle, OTV nozzle or the NASA LeRC 1030:1 nozzle. This would demonstrate the application and assist in the validation of the code. Probably the blocked version of the code would have to be used.

The second option would be to increase the capability of the PARC code. Improvements of interest would be the addition of nozzle performance, equilibrium H_2/O_2, turbulence models for separation, rarefaction, relaminarization and non-equilibrium.

The final option would be to develop the capability to use the code for novel nozzle concepts, such as for altitude compensating nozzles.

These options are not mutually exclusive and it is expected that progress will be made in all areas next year with emphasis being placed on only one of them.

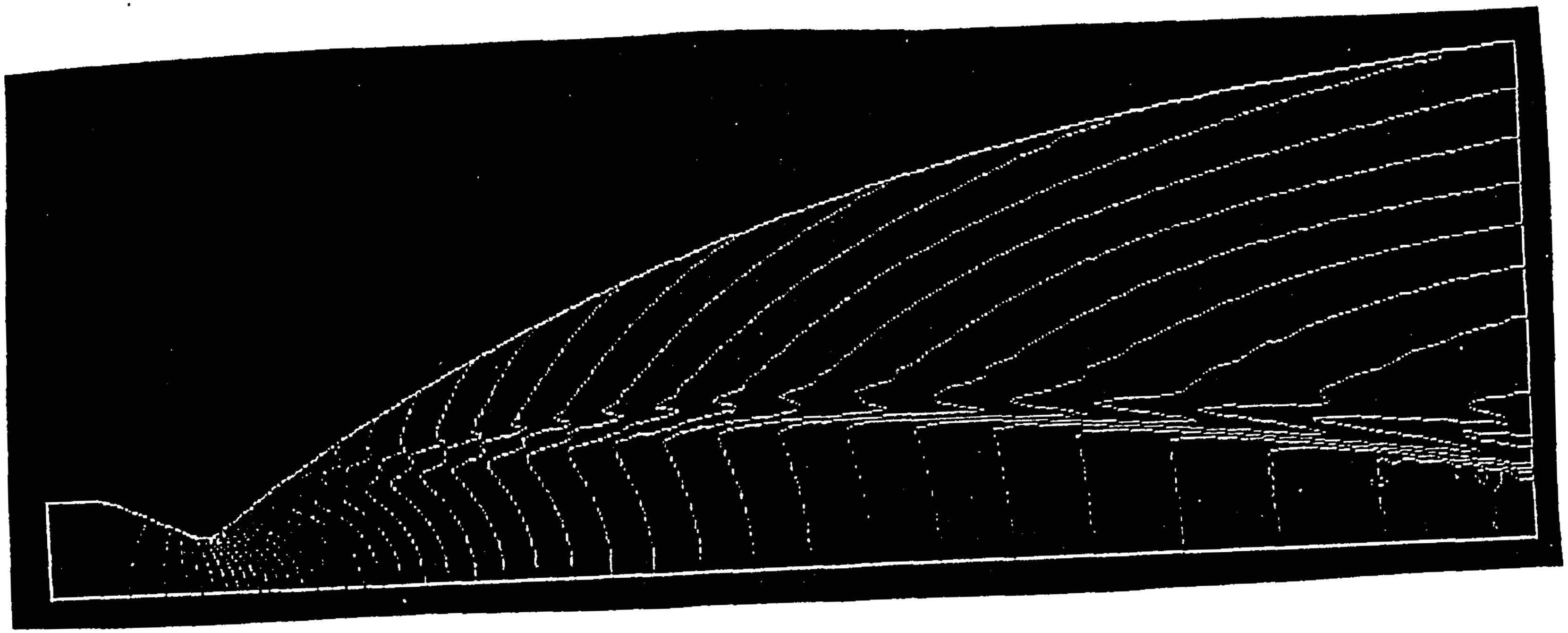


Figure 4.5-1 a. PARC2D computations of SSME engine flow field assuming inviscid, constant gamma conditions.

a) Constant Mach number contours for entire engine. Figure was made on IRIS.

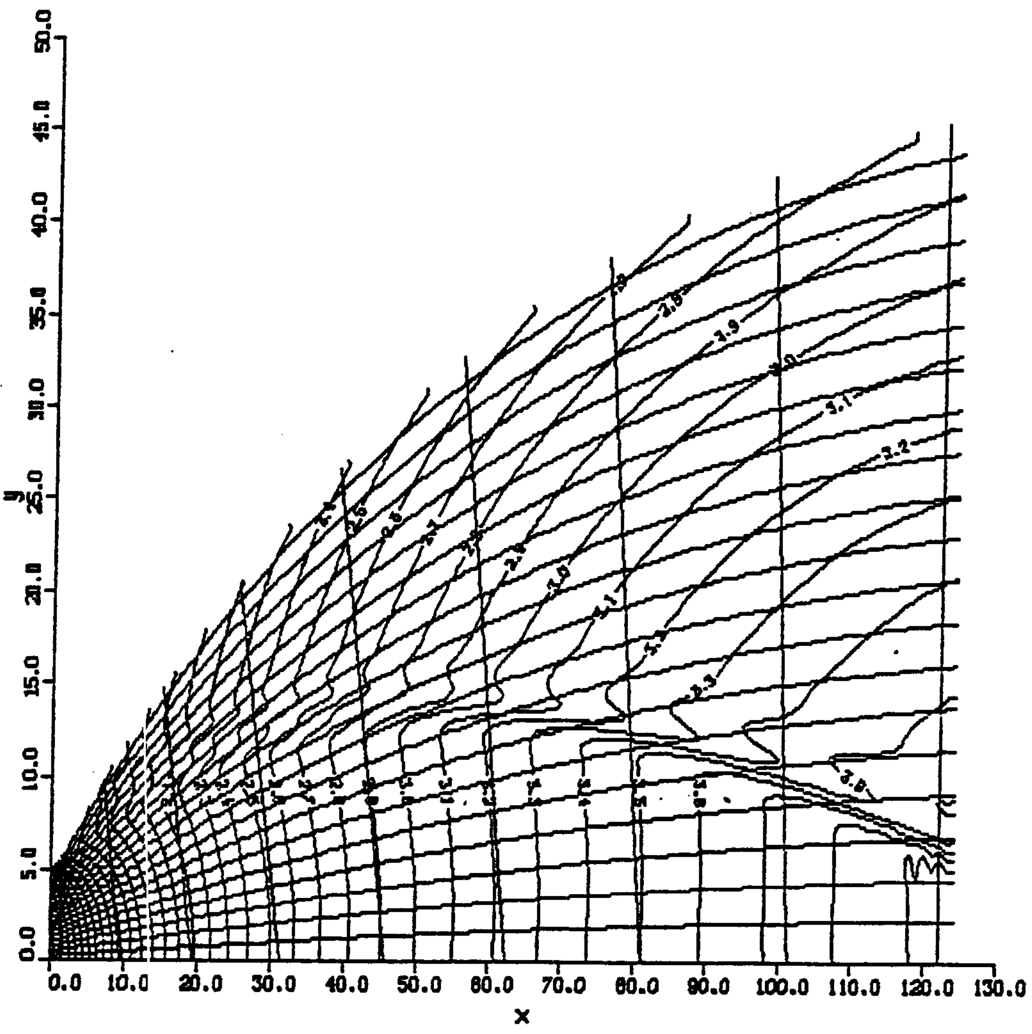


Figure 4.5-1 b. Constant Mach number contours using PLOT3D.

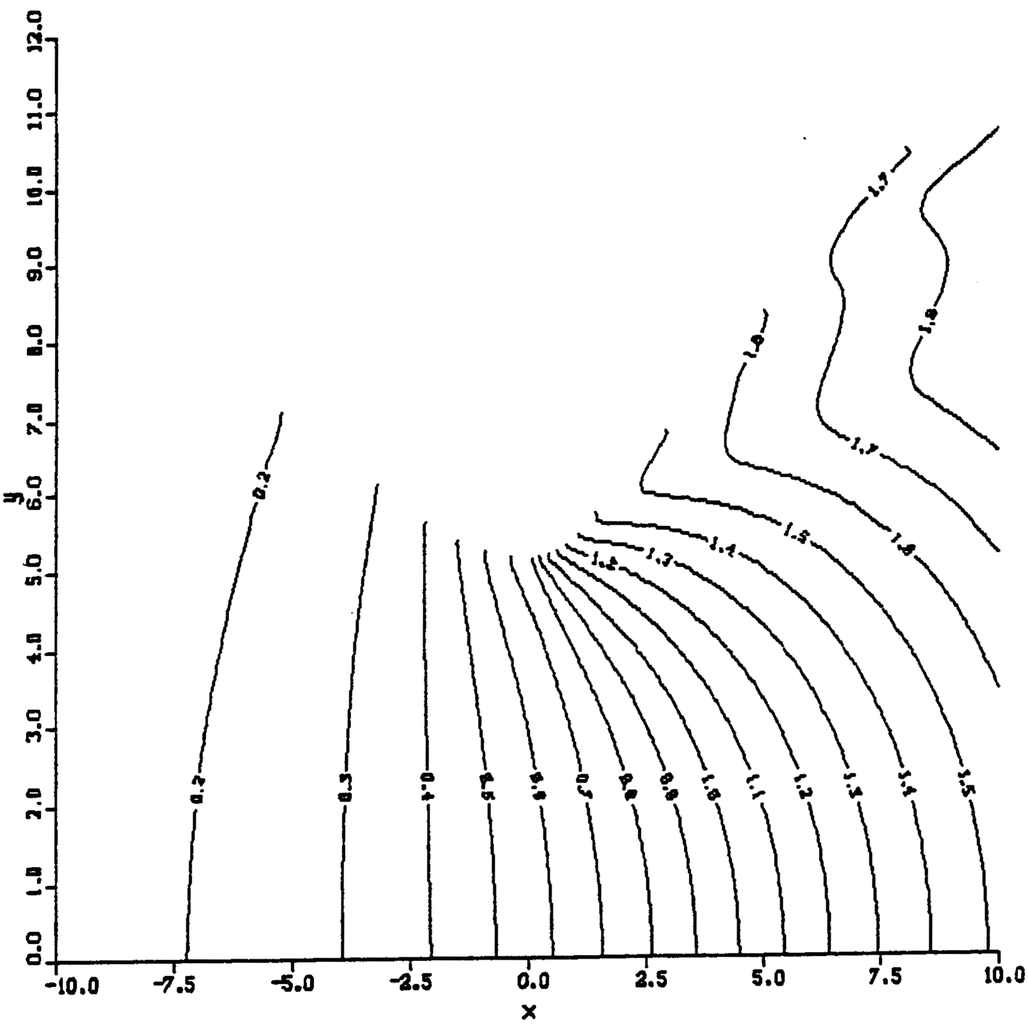


Figure 4.5 Constant Mach number contours in region of SSME
1-c engine throat.

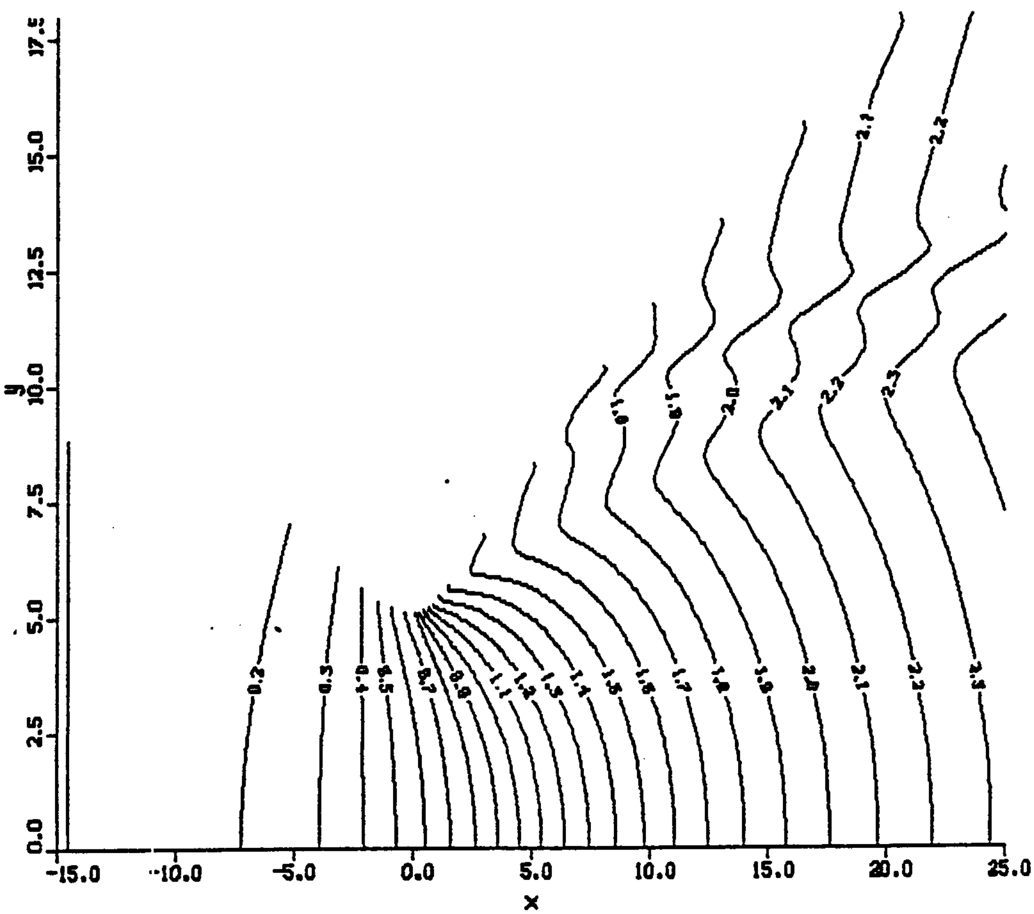
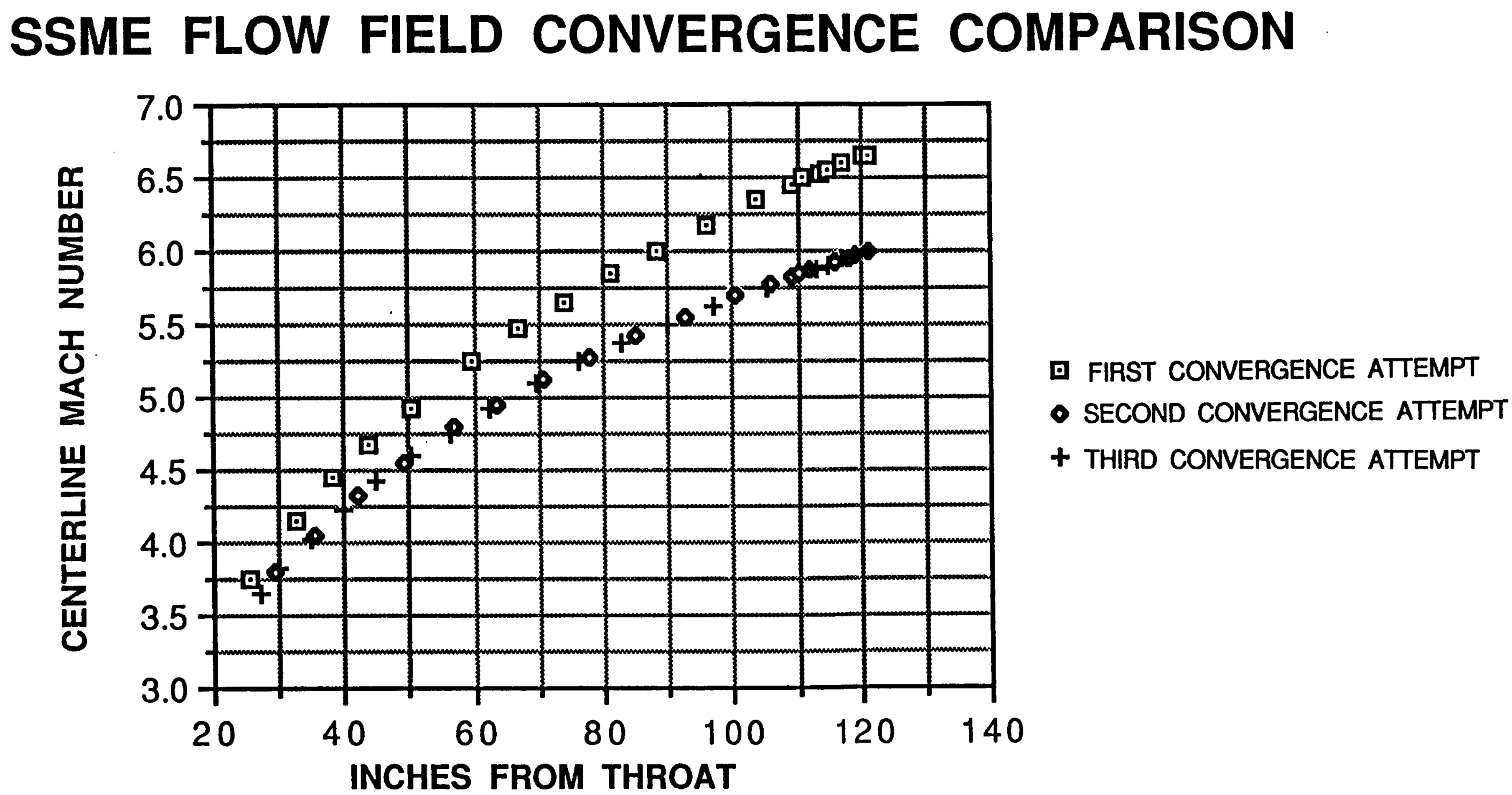


Figure 4.5-1 d) Constant Mach number contours downstream of throat in SSME engine showing formation of embedded shock wave



SSME FLOW FIELD CONVERGENCE COMPARISON
CENTERLINE MACH NUMBER
7.0
6.5
6.0
5.5
5.0
4.5
4.0
3.5
3.0
20
40
60
80
100
120
140
INCHES FROM THROAT
FIRST CONVERGENCE ATTEMPT
SECOND CONVERGENCE ATTEMPT
THIRD CONVERGENCE ATTEMPT

Figure 4.5 2 a.

SSME FLOW FIELD CONVERGENCE COMPARISON

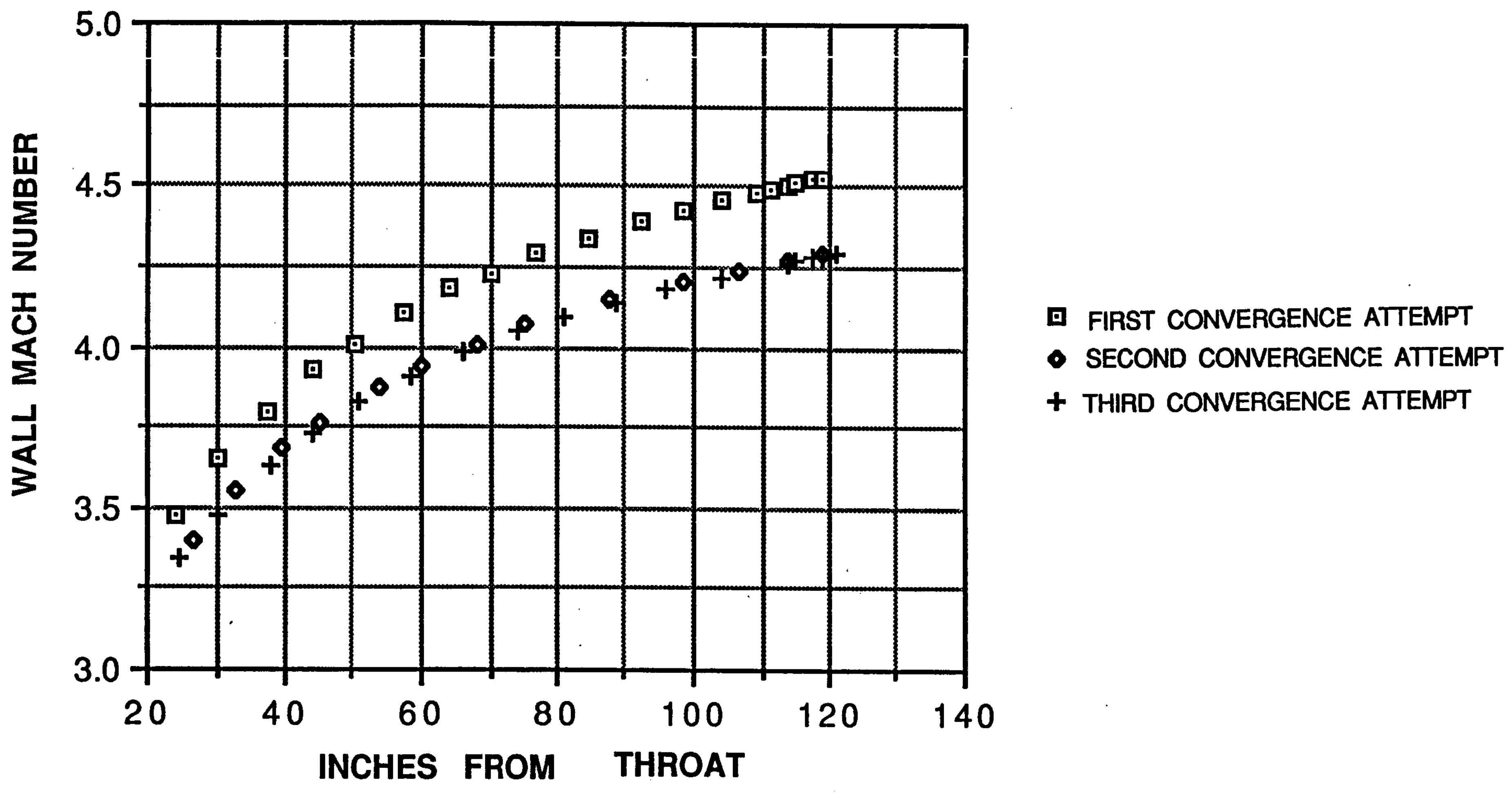
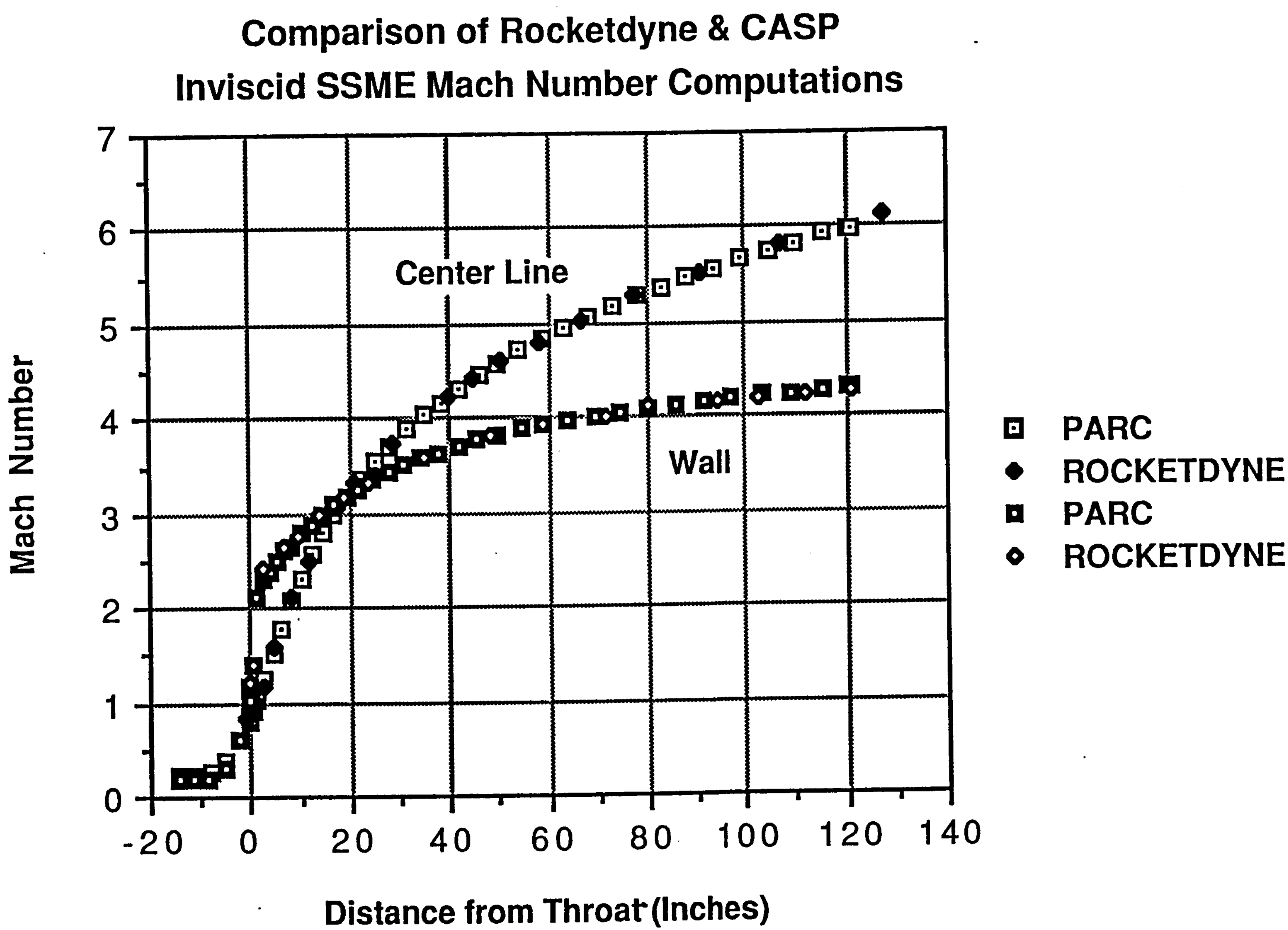


Figure 4.5 2 b.


Comparison of Rocketdyne & CASP
Inviscid SSME Mach Number Computations
Mach Number
0
1
2
3
4
5
6
7
-20
0
20
40
60
80
100
120
140
Distance from Throat (Inches)
Center Line
Wall
PARC
ROCKETDYNE
PARC
ROCKETDYNE

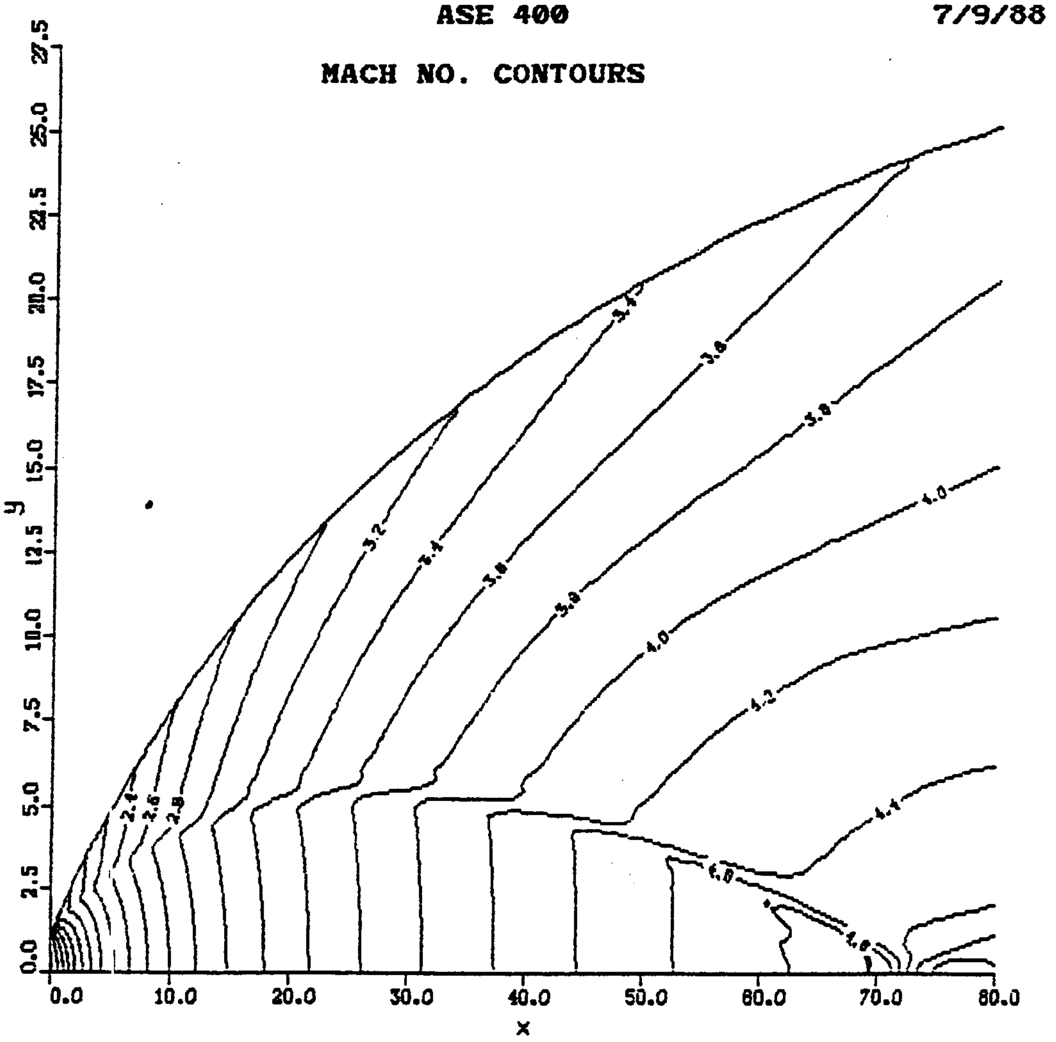


Figure 4.5-4 PARC2D computations of ASE engine flow field assuming inviscid, constant gamma conditions

a) Constant Mach number contours for downstream portion of engine.

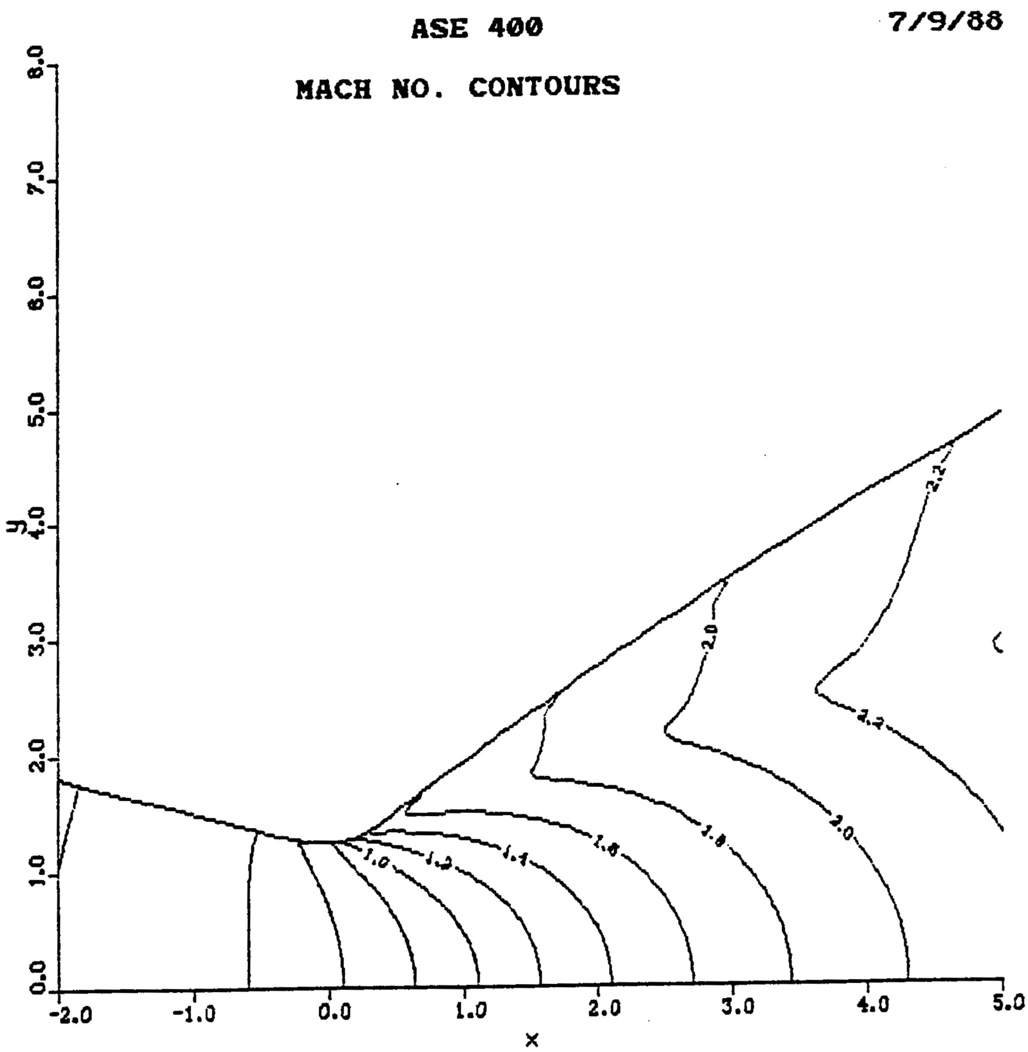


Figure 4.5-4 b) Constant Mach number contours in region of ASE engine throat.

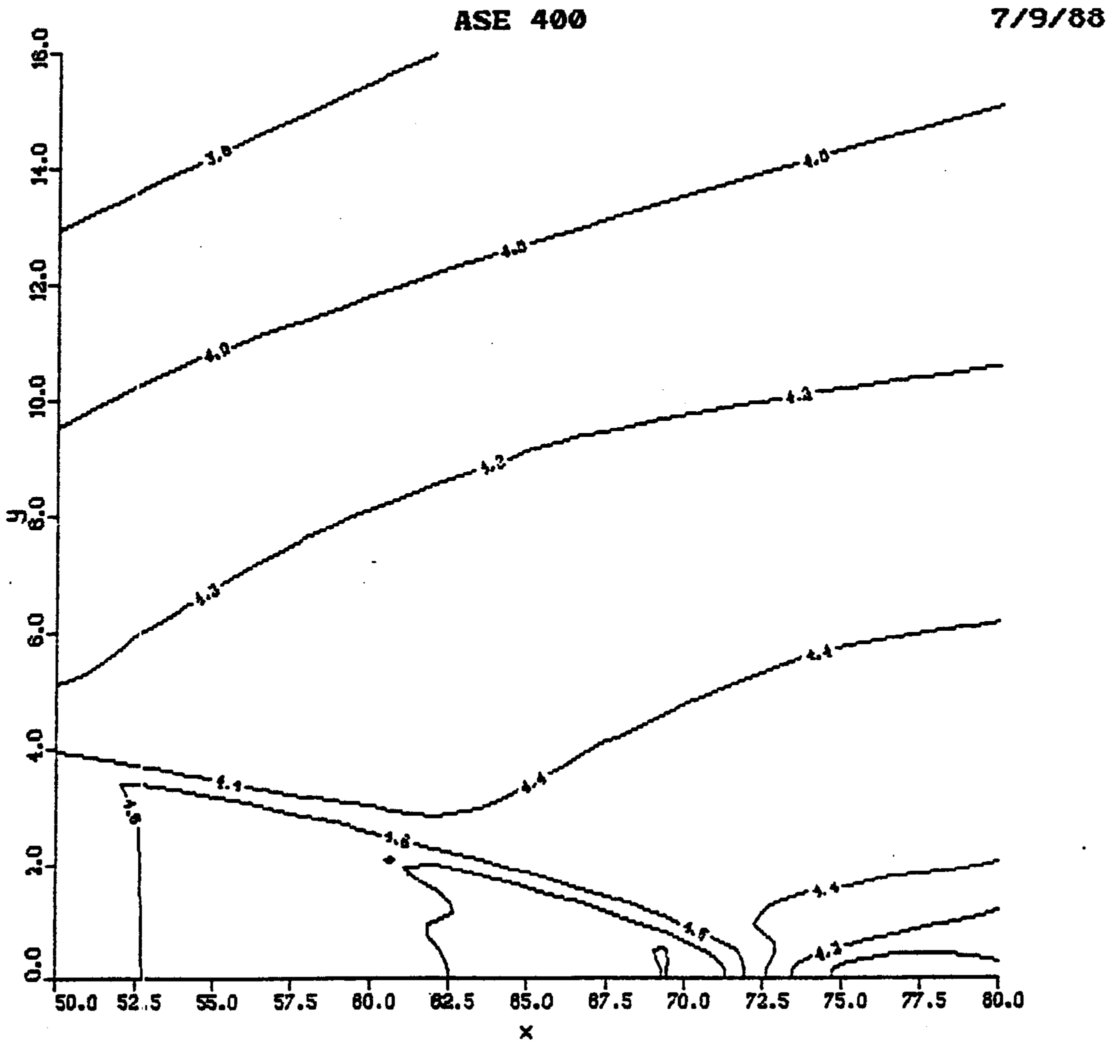
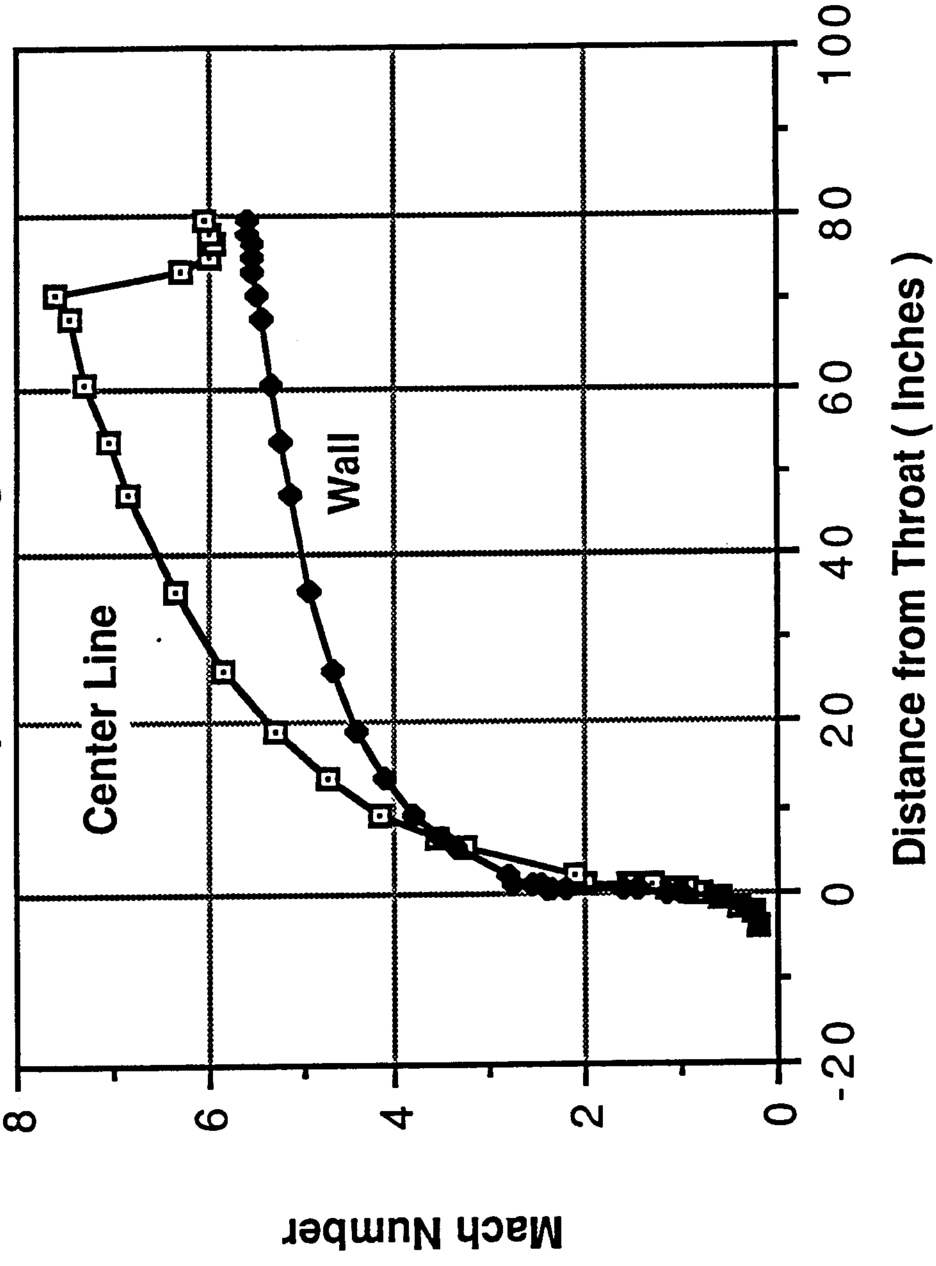


Figure 4.5-4 c) Constant Mach number contours in region of ASE engine exit plane.

ASE Inviscid Mach Number Distributions Computed Using PARC 2D



ASE Inviscid Exit Mach Number Profile
Computed Using PARC 2D

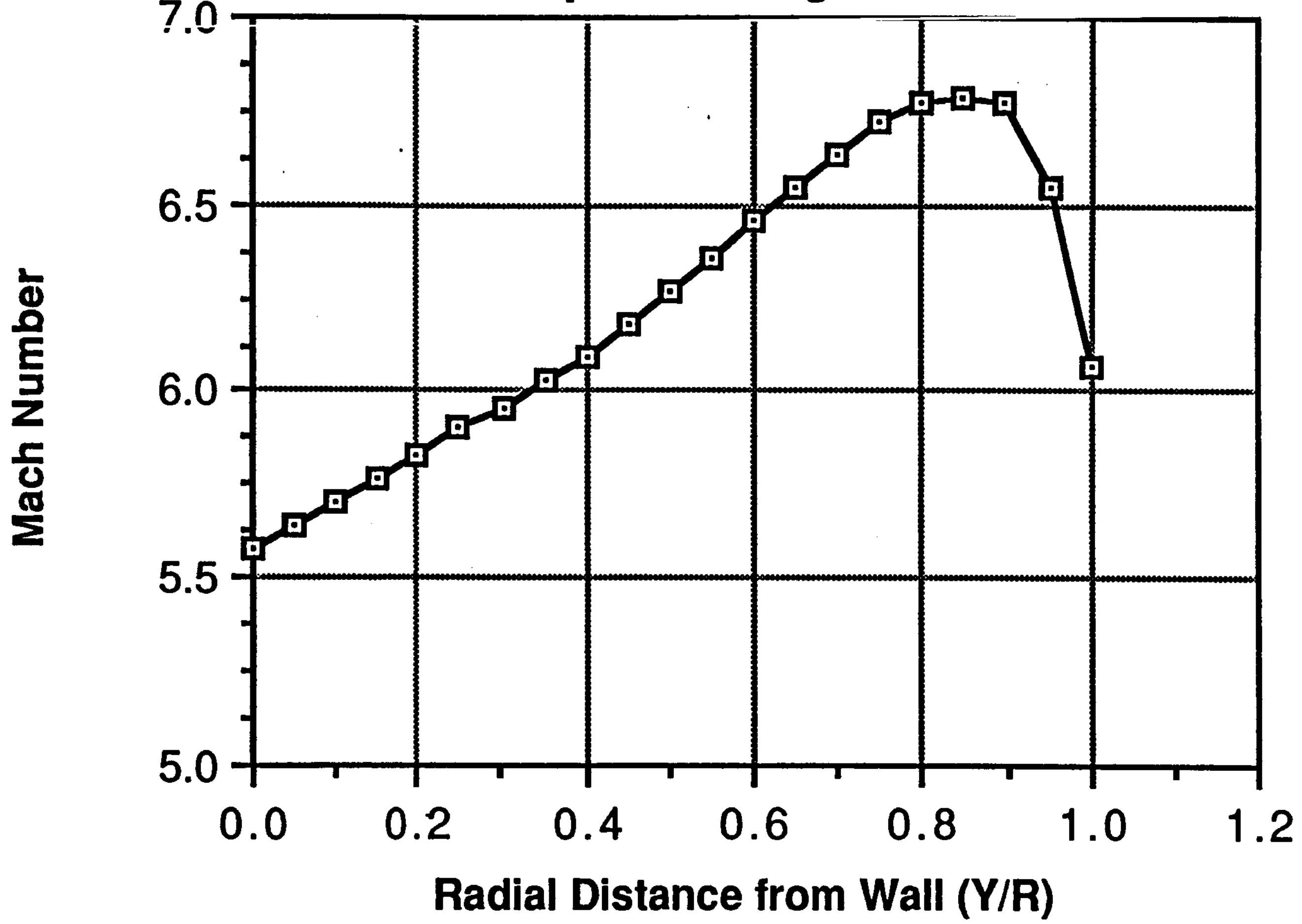


Figure 4.5-6

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SSME COMPONENT ASSEMBLY & LIFE MANAGEMENT EXPERT SYSTEM (CALMES)

SECTION 4.6

4.6 SSME COMPONENT ASSEMBLY & LIFE MANAGEMENT EXPERT SYSTEM (CALMES)

4.6.1 Principal Investigators:

DR. MOONIS ALI, CASP/UTSI
MR. ARNOLD M. NORMAN, ROCKETDYNE DIV., ROCKWELL INTERNATIONAL CORPORATION

Other Investigators:

MR. BILL DIETZ, CASP/CALSPAN
MR. HARRY FERBER, CASP/UTSI GRA
MR. AL DAUMANN, ROCKETDYNE
MR. BRUCE MAYNARD, ROCKETDYNE

4.6.2 Objective:

The objective of this project is to develop an expert system to 1) assess the remaining life of space shuttle main engine (SSME) components following each ground test or flight mission, 2) determine a near-optimal schedule for ground testing and component assembly, and 3) create a near-optimal assembled component inventory (e.g. oxidizer and fuel pumps) from the inventory of available basic components. CALMES is designed to assist Rocketdyne in the activities which involve many logistical problems which must be addressed to meet flight schedules, such as engine assembly and ground test scheduling. CALMES will assist in the engine assembly and scheduling process, and will insure that these activities utilize available resources as optimally as is possible.

The commercial product will be expert system software that can be used for tracking propulsion system components and for system test and flight scheduling.

4.6.3 Approach:

The overall problem being addressed by the expert system may be summarized by the following steps:

a) Given an inventory of parts (e.g. turbine blades), assemble major components (e.g. turbopumps).

b) From the inventory of major components resulting from step 1), assemble a fleet of engines.

c) Perform ground tests on the assembled engines.

d) Assign engines which have passed required ground testing to shuttle flights.

All of the above steps must be performed subject to many constraints. For example, the major components and engines must be assembled from parts which will result in engines with allowable lifetimes sufficient to accommodate the desired flight schedule. Resources such as test stands and assembly benches must be scheduled to meet flight deadlines, testing requirements, and time restrictions. Also, engines must be assigned to flight vehicles in a manner which minimizes engine changes over the proposed flight schedule.

Constraints on the assembly and scheduling processes may be categorized as being either hard or soft. Hard constraints are inviolable; an example is a requirement of three months between the completion of a test on an engine and the use of that engine in flight. Soft constraints are preferences which may be enforced or relaxed to accommodate hard constraints. An example of a soft constraint is the preferred use of a particular test stand for certain types of tests, or the use of as few assembly benches as possible during assembly of a major component. The approach used in the present work allows the incorporation of both hard and soft constraints into the assembly and scheduling process. In addition, soft constraints may be given relative degrees of importance.

The overall approach used in the CALMES design accommodates the overall problem as outlined by Rocketdyne. However, the following simplifying assumptions have been made for the purposes of prototyping:

a) A single type of major component (high-pressure oxidizer turbopumps, or HPOTPs) is considered. More major components will be considered in the operational program.

b) HPOTPs are assumed to consist of five life-limiting parts, i.e. blades, impeller, housing, shaft, and turbine disc. Additional parts may be considered in the operational program.

c) A single launch vehicle is assumed. The operational program will consider three launch vehicles.

d) Only green run (e.g. component flight certification) tests are scheduled. Engine certification and development tests, etc. are not presently incorporated into test schedules.

4.6.4 Accomplishments In FY88:

CASP developed the expert system prototype on the basis of the data provided by Rocketdyne. The expert system's knowledge base includes a complete parts inventory and proposed flight schedule. Two input files are supplied by the user: 1) the parts inventory, which contains information about each part which is available for assembly, and 2) a flight schedule, containing flight times and durations of future flights. At present, the parts inventory is generated by a program which assigns serial numbers, allowable life estimates, and allowable starts to each part randomly. The flight schedule is generated by the user. The system performs the following operations:

a) Assignment Of Parts To Pumps

The part assignment process is illustrated in Figs. 4.6-1through 4.6-3. Figure 4.6-1 shows the assignment of blade sets to individual pumps, which are designated in the last column by alphabetic characters. The first entry states that the second blade set (serial number 1000002, allowable life of 1723 seconds, 9 allowable starts) is assigned to pump "T". Since only a single major component (high pressure oxidizer turbopump) is considered, "T" is used as an engine designation as well. At the bottom of Fig. 1 are blade sets which are not assigned to any pump or engine. Assignments for the remaining four parts are performed in a similar manner.

Parts are assigned to pumps in a manner which ensures an optimal pump fleet, in the sense that no rearrangement of parts will result in a mix of pumps with greater allowable lifetimes. The assignment algorithm allows pump fleets to be optimized on the basis of life, starts, or an arbitrary combination of desirable factors.

Figure 4.6-2 is a table summarizing the pump fleet resulting from the parts assignments. Forty-seven pumps can be assembled from the parts inventory, with allowable lifetimes from 2324 hours to 79 hours. As stated above, this is the best possible mix of pumps which can be obtained from the given parts inventory. Fig. 4.6-3 summarizes parts to pump assignment and details which parts (by serial number) are assigned to each pump.

The assignment of parts to pumps does not imply that all of the pumps should actually be assembled. Rather, the part assignment represents a "virtual" pump fleet. Which pumps are actually assembled will depend on which pumps are actually required by the flight schedule.

b) Assignment Of Engines To Flights

Once the parts have been assigned to pumps and engines, assignment of engines to flights can be performed. The top of Fig. 4 depicts 1) the input flight schedule (provided by the user), and 2) the assignment of engines to each scheduled flight. The input flight schedule is not realistic, as it schedules a shuttle flight each week from week 55 to week 66. However, it is included as an example as a "worst case" scenario, in that it is most demanding of ground test and component assembly resources.

The assignment of engines to flights is depicted graphically in a timeline format spanning 70 weeks. E1, E2 and E3 are labels designating the three engine locations on the orbiter. The assignment graph indicates that engine "F" is assigned to flights 2, 3, and 4, while engine "T" is assigned to flights 1 and 2. The engine-flight assignment algorithm allows engines to be assigned to flights in a preferential manner. In the example, single engines are to be assigned to as many flights as possible, with early flights taking precedence over later ones. Other preferences may be included if desired.

c) Engine Test Scheduling

Once engine-flight assignments are made, engine test scheduling is performed. The results of scheduling engine tests for the given flight schedule is illustrated by the timelines depicted in Figure 4.6-5. The flight schedule timeline is repeated for comparison. A hard constraint requiring three months between an engine test and flight must be accommodated by the test schedule. In addition, two soft constraints are imposed, i.e. it is preferred that tests occur on test stand B-1, no earlier than four months before the flight. The hard and soft constraints are accommodated by the schedule depicted in Figure 4.6-5. Note that some tests were scheduled for test stand A-2 so that no test is performed earlier than four months before the flight.

d) Pump Assembly Scheduling

The final step, scheduling of pump assemblies, is depicted in Figure 4.6-6. As in the previous step, the scheduling algorithm allows preferences to be accommodated if possible. In this example, it is desired to schedule assemblies as late as possible, using as few assembly benches as possible. (Alternatively, a user could prefer to fill up all benches if possible, to only use certain benches during certain periods, or assembly times, etc.) In the example, all required pumps can be assembled in time for their green run tests. Four assembly benches are required for the pump assembly.

4.6.5 Current Status:

The work accomplished so far on the SSME Component Assembly & Life Management Expert System has produced a prototype which successfully demonstrates the application of the scheduling and part assignment approach to the problem Rocketdyne has outlined. The prototype also demonstrates the accommodation of hard and soft constraints in the engine assembly and scheduling processes. However, the prototype was developed to address a subset of the overall problem. Development of the prototype also raised issues related to 1) the scheduling criteria to be used; 2) program efficiency; and 3) integration of the scheduling program into the existing Rocketdyne computer facilities. The prototype and documentation have been delivered to Rocketdyne.

4.6.6 Publications:

1. W.E. Dietz, H.J. Ferber, M. Ali, "SSME Component Assembly, Assignment and Scheduling Expert System", to be presented at the 2nd International Conference on Industrial Applications of Artificial Intelligence/Expert Systems, June 6-9, 1989.

4.6.7 Future Work:

Future work will involve 1) expansion of the capabilities of the prototype; 2) refinement of schedule optimization criteria; 3) increase of program efficiency and speed; 4) implementation of common sense reasoning based on the domain knowledge which will be acquired from human experts; and 5) integration of the operational scheduling system into the existing Rocketdyne facilities.

The approach used in the prototype allows flexibility in terms of what optimizing criteria are applied to the scheduling and part/pump assignment. For instance, schedules can be generated which attempt to optimize 1) the number of assembly benches used for part assembly, or 2) the overall time required for all assemblies. Similarly, other optimizing criteria have been identified for part assignment, pump flight assignments and test scheduling. These criteria can in principle be adjusted by the program user to generate schedules and assignments based on various optimizing criteria. The prototype system at present defaults to preset optimizing criteria. These criteria will be incorporated as options in the operational program. The range of possible optimizing criteria has not been fully explored; much further work is possible in this area.

The scheduling and assignment algorithms used in the prototype attempt to generate globally optimum schedules and part assignments; as a result, they can be time-consuming when given large part inventories and flight schedules. Further work will be done to insure that the algorithms are applied as effectively and efficiently as is possible. The application of domain heuristics and knowledge-based reasoning to increase the efficiency of the scheduling and assignment process will be investigated.

At present, the prototype uses part inventories and flight assignments generated locally as test cases. The operational scheduling system will interact with existing Rocketdyne inventory databases. An effort will be undertaken to integrate the operational system into existing Rocketdyne computer systems without impacting Rocketdyne operations.

PART-PUMP ASSIGNMENTS

BLADES PART	NAME	S/N	LIFE	STARTS	PUMP/ENGINE (U/N)
2	BLADES	1000002	1723	9	T
3	BLADES	1000003	1020	3	c
7	BLADES	1000007	1951	13	M
9	BLADES	1000009	2003	12	I
10	BLADES	1000010	773	7	h
12	BLADES	1000012	579	13	n
13	BLADES	1000013	681	5	l
14	BLADES	1000014	1102	5	z
15	BLADES	1000015	701	13	k
16	BLADES	1000016	1830	15	R
20	BLADES	1000020	946	11	e
23	BLADES	1000023	782	11	g
24	BLADES	1000024	1859	3	P
31	BLADES	1000031	403	15	s
33	BLADES	1000033	679	5	m
35	BLADES	1000035	2185	15	F
36	BLADES	1000036	349	7	t
37	BLADES	1000037	1077	1	a
42	BLADES	1000042	984	13	d
44	BLADES	1000044	1906	8	O
46	BLADES	1000046	2348	9	B
47	BLADES	1000047	1465	1	V
49	BLADES	1000049	1984	4	J
53	BLADES	1000053	765	3	i
54	BLADES	1000054	1408	3	X
55	BLADES	1000055	467	2	r
56	BLADES	1000056	2063	12	H
58	BLADES	1000058	2239	6	D
59	BLADES	1000059	2071	4	G
60	BLADES	1000060	1440	10	W
61	BLADES	1000061	2219	12	E
62	BLADES	1000062	895	13	f
64	BLADES	1000064	529	15	o
65	BLADES	1000065	742	9	j
67	BLADES	1000067	221	5	u
69	BLADES	1000069	1035	1	b
70	BLADES	1000070	1849	15	Q
72	BLADES	1000072	1972	8	L
73	BLADES	1000073	1214	9	Y
74	BLADES	1000074	2281	6	C
76	BLADES	1000076	474	13	q
80	BLADES	1000080	2385	7	A
81	BLADES	1000081	509	15	p
82	BLADES	1000082	1975	15	K
87	BLADES	1000087	1791	1	S
88	BLADES	1000088	1549	1	U
89	BLADES	1000089	1929	2	N

UNASSIGNED PARTS

PART	NAME	S/N	LIFE	STARTS
1	BLADES	1000001	1317	10
4	BLADES	1000004	988	13
5	BLADES	1000005	2187	3
6	BLADES	1000006	2298	5
8	BLADES	1000008	2082	11
11	BLADES	1000011	791	12
17	BLADES	1000017	2293	6
18	BLADES	1000018	2410	7
19	BLADES	1000019	2436	13
21	BLADES	1000021	337	13
22	BLADES	1000022	11	15
25	BLADES	1000025	1599	15
26	BLADES	1000026	1261	2
27	BLADES	1000027	2089	2
28	BLADES	1000028	1224	3
29	BLADES	1000029	1106	9
30	BLADES	1000030	1251	1
32	BLADES	1000032	2161	13
34	BLADES	1000034	859	11
38	BLADES	1000038	2124	4
39	BLADES	1000039	2127	14
40	BLADES	1000040	2454	7
41	BLADES	1000041	231	12
43	BLADES	1000043	62	10
45	BLADES	1000045	78	8
48	BLADES	1000048	2022	15
50	BLADES	1000050	9	1
51	BLADES	1000051	1551	5
52	BLADES	1000052	1467	4
57	BLADES	1000057	2296	9
63	BLADES	1000063	1317	8
66	BLADES	1000066	261	11
68	BLADES	1000068	907	14
71	BLADES	1000071	2429	2
75	BLADES	1000075	1376	9
77	BLADES	1000077	2423	10
78	BLADES	1000078	2107	1
79	BLADES	1000079	2037	1
83	BLADES	1000083	1278	4
84	BLADES	1000084	2110	13
85	BLADES	1000085	1293	11
86	BLADES	1000086	1141	6
90	BLADES	1000090	826	2
91	BLADES	1000091	2133	14
92	BLADES	1000092	1494	1
93	BLADES	1000093	858	11
94	BLADES	1000094	2409	10
95	BLADES	1000095	350	8
96	BLADES	1000096	376	2

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Figure 4.6-1 ASSIGNMENT OF PARTS (BLADE SETS) TO PUMPS

PUMP-ENGINE ASSIGNMENTS

INSTANCE	PUMP	U/N	LIFE	STARTS	ENGINE
1	HPOTP	2000059	2324	1	A
2	HPOTP	2000027	2311	4	B
3	HPOTP	2000021	2259	3	C
4	HPOTP	2000064	2229	2	D
5	HPOTP	2000091	2203	1	E
6	HPOTP	2000015	2184	5	F
7	HPOTP	2000095	2067	4	G
8	HPOTP	2000072	2053	3	H
9	HPOTP	2000035	1914	3	I
10	HPOTP	2000002	1856	4	J
11	HPOTP	2000067	1843	3	K
12	HPOTP	2000005	1817	4	L
13	HPOTP	2000074	1796	5	M
14	HPOTP	2000028	1732	2	N
15	HPOTP	2000049	1714	3	O
16	HPOTP	2000023	1706	2	P
17	HPOTP	2000070	1706	6	Q
18	HPOTP	2000007	1668	7	R
19	HPOTP	2000054	1626	1	S
20	HPOTP	2000052	1616	2	T
21	HPOTP	2000045	1525	1	U
22	HPOTP	2000073	1462	1	V
23	HPOTP	2000097	1408	1	W
24	HPOTP	2000024	1391	3	X
25	HPOTP	2000069	1192	2	Y
26	HPOTP	2000077	1068	2	Z
27	HPOTP	2000042	1007	1	a
28	HPOTP	2000034	993	1	b
29	HPOTP	2000055	990	2	c
30	HPOTP	2000083	938	1	d
31	HPOTP	2000089	934	4	e
32	HPOTP	2000076	865	2	f
33	HPOTP	2000001	746	1	g
34	HPOTP	2000025	731	3	h
35	HPOTP	2000090	723	1	i
36	HPOTP	2000029	709	3	j
37	HPOTP	2000020	639	1	k
38	HPOTP	2000032	628	3	l
39	HPOTP	2000053	564	1	m
40	HPOTP	2000011	509	2	n
41	HPOTP	2000013	434	2	o
42	HPOTP	2000018	427	1	p
43	HPOTP	2000044	401	3	q
44	HPOTP	2000009	398	2	r
45	HPOTP	2000046	389	3	s
46	HPOTP	2000031	345	3	t
47	HPOTP	2000094	79	1	u

Figure 4.6-2 OPTIMAL PUMP INVENTORY

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PUMP-PART ASSIGNMENTS

ENGINE	BLADES	HOUSING	SHAFT	TURBINE DISC	MAIN IMPELLER
A	1000080	2000059	3000018	4000042	5000014
B	1000046	2000027	3000025	4000021	5000037
C	1000074	2000021	3000032	4000054	5000012
D	1000058	2000064	3000013	4000058	5000030
E	1000061	2000091	3000038	4000078	5000009
F	1000035	2000015	3000029	4000010	5000016
G	1000059	2000095	3000031	4000068	5000026
H	1000056	2000072	3000010	4000081	5000031
I	1000009	2000035	3000035	4000067	5000027
J	1000049	2000002	3000045	4000080	5000047
K	1000082	2000067	3000036	4000065	5000046
L	1000072	2000005	3000042	4000001	5000013
M	1000007	2000074	3000052	4000026	5000017
N	1000089	2000028	3000012	4000051	5000001
O	1000044	2000049	3000019	4000032	5000002
P	1000024	2000023	3000050	4000070	5000005
Q	1000070	2000070	3000011	4000049	5000025
R	1000016	2000007	3000021	4000055	5000010
S	1000087	2000054	3000048	4000039	5000018
T	1000002	2000052	3000047	4000066	5000036
U	1000088	2000045	3000015	4000028	5000035
V	1000047	2000073	3000023	4000027	5000024
W	1000060	2000097	3000022	4000076	5000033
X	1000054	2000024	3000024	4000029	5000022
Y	1000073	2000069	3000027	4000046	5000032
Z	1000014	2000077	3000007	4000036	5000019
a	1000037	2000042	3000039	4000003	5000008
b	1000069	2000034	3000033	4000014	5000021
c	1000003	2000055	3000014	4000034	5000044
d	1000042	2000083	3000049	4000050	5000029
e	1000020	2000089	3000008	4000060	5000040
f	1000062	2000076	3000044	4000059	5000011
g	1000023	2000001	3000006	4000013	5000042
h	1000010	2000025	3000043	4000038	5000020
i	1000053	2000090	3000004	4000008	5000003
j	1000065	2000029	3000030	4000023	5000006
k	1000015	2000020	3000051	4000071	5000034
l	1000013	2000032	3000009	4000011	5000023
m	1000033	2000053	3000037	4000077	5000039
n	1000012	2000011	3000040	4000030	5000041
o	1000064	2000013	3000034	4000043	5000004
p	1000081	2000018	3000054	4000041	5000007
q	1000076	2000044	3000005	4000015	5000043
r	1000055	2000009	3000026	4000037	5000015
s	1000031	2000046	3000017	4000048	5000028
t	1000036	2000031	3000053	4000064	5000038
u	1000067	2000094	3000003	4000056	5000045

Figure 4.6-3 PART-TO-PUMP ASSIGNMENT TABLE

```
                         FLIGHT SCHEDULE
E-1  ......................................................TTGGGeQQKKRR....
E-2  ......................................................fFFFHHHNNCCC....
E-3  ......................................................XXdIIIcBBBPP....
     0000000001111111111222222222233333333334444444444555555555566666666667
     1234567890123456789012345678901234567890123456789012345678901234567890
                               WEEK
```

FIG 4. ENGINE-TO-FLIGHT ASSIGNMENT TIMELINE

```
                          TEST SCHEDULE
A-1  ......................................................................
A-2  ...........................................d...cB..P..................
B-1  .......................................XfTFGIHeQNKCR..................
     0000000001111111111222222222233333333334444444444555555555566666666667
     1234567890123456789012345678901234567890123456789012345678901234567890
                               WEEK

                         FLIGHT SCHEDULE
E-1  ......................................................TTGGGeQQKKRR....
E-2  ......................................................fFFFHHHNNCCC....
E-3  ......................................................XXdIIIcBBBPP....
     0000000001111111111222222222233333333334444444444555555555566666666667
     1234567890123456789012345678901234567890123456789012345678901234567890
                               WEEK
```

FIG 5. TEST SCHEDULE TIMELINE

```
                        ASSEMBLY SCHEDULE
AL-6  .GGGGGGGGGGffffffffffTTTTTTTTTTFFFFFFFFFFRRRRRRRRRR...................
AL-5  .QQQQQQQQQQIIIIIIIIIIHHHHHHHHHHeeeeeeeeeePPPPPPPPPP...................
AL-4  ccccccccccNNNNNNNNNNKKKKKKKKKKddddddddddCCCCCCCCCC....................
AL-3  ............................XXXXXXXXXXBBBBBBBBBB......................
AL-2  ......................................................................
AL-1  ......................................................................
      0000000001111111111222222222233333333334444444444555555555566666666667
      1234567890123456789012345678901234567890123456789012345678901234567890
                                WEEK

                          TEST SCHEDULE
A-1   ......................................................................
A-2   ...........................................d...cB..P..................
B-1   .......................................XfTFGIHeQNKCR..................
      0000000001111111111222222222233333333334444444444555555555566666666667
      1234567890123456789012345678901234567890123456789012345678901234567890
                                WEEK
```

Figure 4.6-4 ASSEMBLY SCHEDULE TIMELINE

4.7 ION ENGINE TESTING

4.7.1 Principal Investigators:

DR. JERE S. MESEROLE, BOEING AEROSPACE COMPANY
MR. ALLAN BAILEY, CASP/CALSPAN

4.7.2 Objective:

The objective of this project is to evaluate requirements for testing high I_{sp} ion engines at simulated space conditions.

The commercial product will be two-fold. First, development of an high I_{sp} thruster is a primary objective and, second, development of test techniques and facilities will be accomplished in the course of developing these thrusters. This testing capability will be a resource for developing/testing thrusters for other organizations.

4.7.3 Accomplishments and Status:

Investigations regarding the testing of ion thrusters have centered on the problems associated with high exhaust velocities. Testing of these devices requires a chamber pressure on the order of 10^{-5} torr or less. The main problem is that even with a lowered mass flow, the exhaust velocity is too high for cryo-cooled surfaces to capture the molecules on first strike. While various approaches have been investigated, a chamber baffling system is seen as the most viable technique to reduce the molecule energy levels to a value suitable for cryogenic pumping. In addition, baffling will minimize the adverse effects of ion engine sputtering on vacuum chamber performance particularly during low thrust or engine shutdown conditions. A computational technique has been identified which can assist in the design of such a baffle system. Dimensioning and detailed design can be initiated when chamber capabilities, interior configuration, and test requirements have been more completely established.

No work is being performed on this project at the present time. Boeing has made a verbal commitment to reinitialize and initiate an effort related to electric propulsion within the next fiscal year. CASP and Boeing are jointly evaluating alternatives with regard to this project and other opportunities in the area of electric propulsion.

4.8 POTENTIAL NEW PROJECTS

During the past year, development has continued on several new initiatives beyond the original six projects. A status report on each of the potential new projects follows:

OMV Variable Thrust Engine Research -

Preliminary definition of the CASP scope of work to support MSFC and TRW in the development of the OMV engine was prepared as a result of two meetings with TRW, MSFC and CASP personnel, one at MSFC January 6, 1988, and the other in Los Angeles on March 11, 1988. Both MSFC and TRW are interested in an advanced CFD model of the single injector combustor flow field in order to be able to extend the applications and fuel compatibility of this basic design. A CFD model is needed that will predict trends in wall temperature and fuel/oxidizer striations as these parameters vary with fuel type and injector configuration. Dr. S-M Jeng, UTSI Faculty Member, will be the Principal Investigator and has submitted a proposal to TRW and MSFC to:

a) develop a CFD model of the TRW VTE single-injector rocket combustor and the combustion process;

b) provide details on the model necessary to understand the theoretical and computational approach; and

c) provide an estimate of the budget and schedule requirements.

It is anticipated that it will take several months to get external funding in-place, however, CASP will initiate this work within the first quarter of FY89 using NASA grant monies.

SSME Leak Detection -

NASA/MSFC identified a requirement for protection of the SSME test hardware during ground testing through identification and analysis of SSME gas leaks. Dr. Roger Crawford, Professor at UTSI, developed a proposal which has been submitted to MSFC and has received verbal acceptance for funding. It is expected this project will be initiated during the first quarter of FY89.

Condition Monitoring Expert System -

Rocketdyne plans to respond to an AFAL RFP (due to be released in May) to perform a laboratory demonstration of an AI system (software, sensors and hardware) applied to a generic propulsion system. CASP will serve as a subcontractor to this effort. Work under the existing CASP project, Fault Monitoring and Diagnostics, will provide a technical base for work anticipated to be performed under the AFAL project. It will be approximately six months before an award is anticipated.

Subscale Fluid Transfer Flight Experiment -

This project is being developed in cooperation with Boeing. MSFC will fund Boeing and CASP will serve as a subcontractor. The objective of the project is to demonstrate a no-vent fill of cryogen liquid into a pre-cooled tank. This is considered a precursor hardware verification experiment for the proposed NASA COLDSAT experiment.

Critical to the experiment will be fluid selection and controlling the pressure transient in the supply tank. A statement of work is presently being developed by Dr. Jere Meserole at Boeing and Dr. Basil Antar at UTSI. It is expected that the project will be initiated in the January-February 1989 time period.

V. CENTER ASSESSMENT

5.1 Synopsis of First Year Achievements:

First year success criteria for a one of a kind endeavor are difficult to quantify. CASP's first year has been marked by growth and establishment of those industrial and NASA interfaces which will guide future development.

We started with six projects which were reduced to five as the year progressed. At the end of the year, the active projects included three with Rocketdyne, one with Boeing and one with Technion. During FY88 we have pursued a number of promising marketing efforts and initiated seven pre-project type activities, six of which are expected to lead to approved projects in the immediate future. Three are with the Marshall Space Flight Center, two with Boeing, one with Rocketdyne, and one with Microcraft/Pratt and Whitney.

In addition, there are seven new proposals that have been formally submitted as follows: two to Rocketdyne, two to Babcock & Wilcox, two to MSFC, and one to TRW. These seven new proposals are awaiting their disposition in FY89.

The following table summarizes the current project status of CASP:

FY88 Projects

Boeing	Fluid Transfer	Basil Antar
Rocketdyne	Spray Combustion	Roy Schulz
Rocketdyne	Component Life	Moonis Ali
Rocketdyne	High Area Ratio	Frank Collins
Technion	MAARC Thruster	George Garrison

FY88 Pre-Project Activities

Boeing	Ion Propulsion	Allan Bailey
Boeing	Fluid Flight Experiment	Basil Antar
Microcraft	Liquid Rocket Specs	Jim Mitchell
MSFC	SSME Leak Detection	Roger Crawford
MSFC	Data Pattern Detection	Moonis Ali
MSFC	OMV Engine Analysis	S.M. Jeng
Rocketdyne	Fault Diagnosis	Moonis Ali

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FY89 New Proposals

Babcock & Wilcox	Fuel Manufacturing in Space	Dwayne McCay
Babcock & Wilcox	Nuclear Electric Propulsion	Bill Baucum
MSFC	Hazardous Gas Detection Hypertext	Ching Lo
MSFC	Fluid Transfer Code	Basil Antar
Rocketdyne	Laser Materials Process.	Dwayne McCay
Rocketdyne	SSME Hypertext	Ching Lo
TRW	OMV Engine Analysis	S.M. Jeng

It is our assessment that the total number of CASP projects in FY89 will grow from the initial five to a minimum of 12 and perhaps as high as 17. This very significant increase will see a corresponding increase in contract value from our industrial partners and MSFC. In FY88 the industrial cash contribution to the total CASP budget was approximately 11%. This number is expected to double in FY89.

The current CASP staffing is 6 faculty, 3 staff and 12 graduate students. The increase expected during next year will result in up to 10 faculty, 6 staff and 19 graduate students by the end of the year. Most of these participants are working part-time in CASP.

During the first year of research activities CASP principal investigators published or presented eight papers associated with space propulsion.

G. Cann & G. Garrison	"Performance Estimates for a Magnetic Annular Arc Thruster"
M. Ali & R. Crawford	"Rocket Engine Control and Monitoring Expert System"
F. Collins, J. Orr & T. Saladino	"PARC Code Development at CASP/UTSI"
G. Garrison	"Establishing a Center for Advanced Space Propulsion"
B. Dietz, W.E. Kiech & M. Ali	"Pattern Based Fault Diagnosis Using Neural Networks"

U. Gupta M. Ali	"Hierarchical Representation and Machine Learning from Faulty Engine Examples To Detect Real Time Abnormal Conditions"
B. Dietz & M. Ali	"Qualitative & Temporal Reasoning in Engine Behavior Analysis and Fault Diagnosis"

5.2 Strategy for the Outyears:

The experience of the first year has clearly established which specific technical disciplines represent the best match of what CASP can offer to industry and what industry (and MSFC) need most:

CHEMICAL PROPULSION

CFD Analysis of rocket engine performance and stability

EXPERT SYSTEM APPLICATIONS

Health Monitoring and Fault Diagnosis
Component Life and Assembly Scheduling
Fault Pattern Detection
Intelligent Hypertext

LOW G FLUID DYNAMICS

2-Phase Fluid Transfer
Fluid Management and Control

ELECTRIC PROPULSION

Magnetic Annular Arc Thruster
Ion Thruster

CASP's future is closely linked with that of our industrial partners and their perception of CASP as a facilitator for application of advances in space propulsion. The financial leverage which the Center offers will be soon overshadowed by our increasing expertise in CASP's areas of primary interest. We will continue to develop leadership in selected but critical aspects of propulsion system evolution. Through a positive impact on system development, we will assure our future as a positive force in the nations' advancements in space.